PETE

IMPACT OF UPSTREAM URBANIZATION ON STREAMS IN PETERSBURG NATIONAL BATTLEFIELD

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INTRODUCTION

Background and Purpose

The Petersburg National Battlefield, located on the eastern side of Petersburg, Virginia, is an historic battlefield site that commemorates the final decisive campaign of the Civil War. The spring of 1864 saw Grant pressing his main objective to break the spirit and resolve of the men in gray - to defeat Lee's Army of Northern Virginia that was defending the Confederate capital of Richmond. When massive assaults on the well-fortified city of Richmond were repulsed, Grant concentrated his forces on Lee's flank at Petersburg in order to cut off the supply lines to the defending army. A long and bloody siege ensued, the longest in U.S. history, as Grant maintained the offensive pressure on Lee's increasingly less effective forces. After a respite in the bloody battles along Petersburg's defensive lines in the winter of 1865, an all-out assault by Grant's forces on April 2, 1865, overran Lee's flank. That night Lee evacuated the remains of his army to the west where the last fateful meeting between the two generals was to occur at Appomattox Courthouse a week later.

Today, the main portion of the Petersburg National Battlefield comprises an area of about 2.5 square miles that is bounded on the south, west, and north by the city of Petersburg and on the east by a U.S. Army installation, Ft. Lee. The battlefield is an island of relative ecosystem stability surrounded by rapidly changing city and military lands. During the Civil War era, much of the rolling upper coastal plain terrain around Petersburg was in agriculture and the Battle of Petersburg was fought across large expanses of open fields. Rows of breastworks protected the defensive positions and provided staging areas for offensive maneuvers. The siege of Petersburg involved several years of large troop encampments, movements of troops and

supplies, and artillery duels that devastated the countryside around the outskirts of Petersburg. Many decades of agricultural use after the war continued the soil compaction and erosion and prevented the natural amelioration of degraded watershed conditions from taking place.

The establishment of Petersburg National Military Park (later renamed Petersburg National Battlefield) on July 3, 1926, and the subsequent purchase of several of the most historically important areas of the original battleground by the National Park Service provided protection for the site and natural regeneration of forests in the open fields began. Today, the area of the original battlefield encompassed by the main core of the Petersburg National Battlefield is predominantly forested with stands of mixed hardwoods or pine-hardwood. Some open meadows are maintained and the principal objective of land management by the National Park Service is to preserve as much of the character of the battlefield as possible against change, both natural and anthropogenic, and to maintain ecosystem stability. Land use adjacent to the boundary of the battlefield ranges from forested to heavily urbanized.

Land use changes outside the battlefield boundary that appeared to be causing undesirable ecosystem changes within it prompted this study. Two small stream systems, Poore Creek and Harrison Creek, that flow south to north through the battlefield have shown signs of change due to changes in watershed conditions upstream of and outside the battlefield. Poore Creek and Harrison Creek, both tributaries of the Appomattox River, drain from headwaters areas that are outside the battlefield to the south. Observations by National Park Service personnel for several years prior to initiation of this study in early 1986, indicated development of instability in the channel of Poore Creek as compared to Harrison Creek. Increased channel erosion was apparent in Poore Creek with extensive lateral and vertical erosion of the channel. The Poore Creek

channel was scoured of most major sediment deposits whereas Harrison Creek had extensive sediment deposits and appeared to be much more stable than Poore Creek. All these signs pointed to changing hydrologic conditions upstream that had caused increased stormflow in Poore Creek and possibly also degraded water quality.

The implications of the hydrologic changes that seemed to have occurred in Poore Creek were that ecosystem changes outside the battlefield were resulting in ecosystem degradation inside the battlefield. Such ecosystem degradation may significantly alter the character of the battlefield, degrade the quality of the experiences available to visitors, and increase the cost of management. Ecosystem alteration resulting from impacts outside a park unit are indicative of the need to address park management on a more comprehensive scale. In this case, the Petersburg National Battlefield occupies portions of two adjacent watersheds. Significant upstream portions of those watersheds that are outside the battlefield boundary are nevertheless having a significant impact on the hydrologic character of the streams within the boundary.

There were significant differences in land use in the headwaters sections of the Poore and Harrison Creek watersheds south of the battlefield in 1986. The Poore Creek watershed had a significantly higher level of development. It was traversed by an interstate highway (I-95) that had up to eight lanes and a major interchange (with U.S. 460) within the watershed. The watershed contained a large shopping center, several large apartment complexes, and a large area of relatively dense residential housing. Major reconstruction activity occurred on I-95 during the early 1980's. The Harrison Creek watershed had several small, relatively low density residential areas, a trailer park, a drive-in theater, a small segment of 4-lane highway (U.S. 460), and a much larger proportion of undeveloped land.

The overall purpose of this project was to study the hydrologic character of the two streams within the battlefield to determine the causes of the apparent hydrologic changes and to recommend management practices to ameliorate those changes. Specific objectives were to:

(1) Measure streamflow in Poore and Harrison Creeks at the point of entry into the battlefield and determine if upstream development had caused increased stormflow in Poore Creek.

(2) Conduct preliminary analyses of the detention basin storage required to ameliorate higher rates of stormflow.

(3) Determine the quality of water in Poore and Harrison Creeks.

(4) Establish baseline stream channel cross-sections and determine if short term changes in stream channel morphology were occurring.

Stream Hydrology and the Impacts of Urbanization

The streamflow regime in any stream is a result of the water balance in the watershed, the temporal and quantitative distribution of rainfall events (and resultant rain free periods), the intensity and duration of individual events, the character of the soils and topography, and the character of the vegetative cover. Total runoff, water available for surface runoff in streams and vertical seepage to regional groundwater systems is controlled by rainfall input and evapotranspiration losses. Total annual streamflow then is controlled by the regimes of rainfall and evapotranspiration and the character of the topography, the soils and the geologic substrata that influence partitioning of total runoff between streamflow and groundwater outflow.

The seasonal variation in streamflow is influenced by the seasonal variation in rainfall and evapotranspiration. Based on long-term averages at Hopewell, Virginia, the annual rainfall of 44.81 in that occurs in the Petersburg area is relatively well distributed throughout the year with

monthly average rainfall amounts in July and August slightly higher than the overall monthly average of 3.73 in (National Oceanic and Atmospheric Administration 1984). The usual seasonal variation in streamflow is thus strongly controlled by variation in evapotranspiration. The seasonal variation in radiant energy availability in an ecosystem and the seasonal changes in interception storage and transpiring surface that occurs with leaf senescence in the fall and foliage development and expansion in the spring are the principle factors that influence seasonal changes in evapotranspiration. The integrated impact of those factors in this region results in seasonal lows of evapotranspiration in January and February, rapid increases in March and April toward the seasonal highs in July and August, and rapid decreases in October and November toward the period of seasonal lows (Gregory and Amatya, unpublished data). Vegetation type has a significant influence on the winter evapotranspiration rates but relatively little during the growing season when leaf area index has reached the annual maximum. In the winter, fallow agricultural fields and dormant hardwood forests have lower evapotranspiration rates than do conifer forests, cool season grasses, or small grains that carry significant leaf area over the winter and that are physiologically active when soil and air temperatures are moderate. Stream baseflows, the sustaining low flows between rainfall events, are normally highest in late winter when the soil storage is fully recharged and evapotranspiration rates are low and are lowest in late summer when soil storage has been depleted and evapotranspiration rates are high.

The short term regime of streamflow in small streams reacts quickly to changing hydrologic conditions in the watershed. Even in undisturbed forested ecosystems, high intensity rainfall results in rapid infiltration of water into the permeable surface layers of the soil and relatively rapid subsurface flow to the channel network. The rapid rise in streamflow that occurs in direct

response to rainfall is known as stormflow. Rainfall intensity and duration, total storm rainfall amount, the depth and permeability of the soils, and the average slope gradients and slope lengths in the watershed influence the character of the stormflow runoff. That runoff can be characterized by a hydrograph, a chart of the time distribution of stream discharge. The rapidity of rise of streamflow in response to the rainfall (slope of the rising limb of the hydrograph), the highest volume of streamflow attained (peak of the hydrograph), and the rate of decline in streamflow after the rain ceases (slope of the recession limb of the hydrograph) are controlled by the integrated net effect of the characteristics of the storm event and the characteristics of the watershed.

Poore Creek and Harrison Creek are typical of small second and third order streams in having high short term variability of streamflow. The relatively small contributing areas of the watersheds with steep slopes and permeable soils, and relatively short lengths of tributaries that contribute flow means that streamflow responds quickly to rainfall. Significant amounts of high intensity rainfall result in large volumes of stormflow with rapid increases in rates of flow to peaks that are many times higher than the average baseflows. Slow outflow of water stored in unsaturated upslope soils and near surface saturated zones near the channel contribute to continued baseflow between rainfall events. High evapotranspiration rates in the summer and early fall may deplete soil storage and lower the water table adjacent to the channel sufficiently to cause cessation of baseflow during extended rain free periods.

The runoff regime of a stream is also strongly affected by land use within the watershed. For a specific watershed and stream system, the lowest relative total annual runoff and the lowest stormflows occur under completely forested conditions with undisturbed soils. Reduction

in evapotranspiration and the soil disturbance that reduces infiltration and increases erosion when forests are converted to agriculture causes increased runoff and stormflows. More drastic changes associated with urbanization where significant areas have no vegetation and are covered by surfaces such as roads, parking lots and roofs that are impervious to infiltration cause even greater increases in total runoff and stormflows.

The morphology of stream channels is a reflection of the substrate of the channel and the character of the runoff. Stream channels tend toward stability when the hydrologic character of the watershed is relatively stable. The erosive power of streamflow is influenced by the volume, velocity, and load of suspended sediment of the flow. The most erosive periodic high flows (1-2 year return period) shape the flow capacity of the channel in small streams. However, the average channel cross-section tends to stabilize at that which is necessary to carry those periodic high flows.

Over geologic time, the channels of small streams slowly erode longitudinally upslope and vertically throughout their length as the general rate of geologic erosion degrades the landscape. Over much shorter time frames, relatively stable streams that flow through erodible substrate continue small dynamic changes in morphology. Lateral variations in velocity and turbulence cause meanders, channel sections where bank erosion is occurring on one side and sediment deposition is occurring on the other side. Deposits of coarse sediment line the channel bottom and are constantly being moved by the higher, more erosive flows. Depth of the channel sediment deposits depends on volume and peak rates of stormflow, input of sediment from surface erosion, variation in longitudinal slope of the channel bottom, the presence of large debris such as boulders and trees, and the variation in erodibility of the channel substrate. Such

channels that are relatively stable usually have vegetation on the upper zone of the sides of the channel because bankfull flows are relatively infrequent. Most of the relatively low rates of lateral erosion in meanders occurs during moderate stormflows.

Destabilization of the channels of small streams results when hydrologic changes in the watershed cause increased runoff and streamflow, particularly increased stormflows. Unusually large storms or years with higher than normal rainfall may temporarily increase channel erosion, increasing channel capacity by increased lateral erosion and scouring of the sediment deposits from the channel bottom. After such occurrences, the sediment deposits will again begin to accumulate and the channel banks will restabilize. Permanent changes in the watershed that result in significant long term increased runoff, particularly increased rates of stormflow, causes dramatic destabilization of stream channels. The higher erosivity of the higher stormflows causes increased lateral and vertical erosion and the channel grows in cross-section.

The process of urbanization is one that dramatically alters a number of different properties of a watershed that affect its hydrologic character (Leopold 1968, Andersen 1970, Schueler 1987). Removal of the natural vegetation reduces evapotranspiration and alters the water balance; less water returns directly to the atmosphere from the soil and ecosystem surfaces and more water is available for runoff. Areas of an urban or suburban environment that are vegetated after the development process is complete usually will have lower potential for evapotranspiration that the agricultural field or forest that preceded them. Soil productivity is usually reduced because of soil disturbance and erosion and the vegetation, regardless of type, has less extensive root development and lower leaf area index than the former ecosystem.

Another change that compounds the impact of reduced evapotranspiration is greatly reduced

infiltration capacity and soil storage for water. Urbanization creates areas in a watershed that are impervious to infiltration such as roofs, parking lots, roads, and driveways. The proportion of an urbanized area that consists of impervious surfaces varies with the intensity and distribution of development, ranging from an average of 85 % impervious area in commercial and business zones to less than 20 % impervious area in low density residential areas with lots larger that 1 acre (USDA Soil Conservation Service 1985, 1986). Urbanization also reduces temporary surface storage for water. Litter and topsoil is removed, surfaces are graded and natural depressions are filled, and soil porosity is reduced by the compaction caused by the operation of heavy machinery.

The efficiency of surface drainage of water is greatly improved by the installation of stormwater drainage systems in developing areas. Such systems that include curbs and gutters, storm drains, culverts, etc. are designed to drain rainwater rapidly from impervious surfaces and transport it rapidly to the nearest natural channel. Channels, natural and man-made, are quite often "improved" to enhance the velocity of water in them and increase their capacity for draining stormflow quickly away from the developed area.

The net effect of the changes in watershed hydrologic characteristics that result from urbanization is a series of changes in stream hydrology (Leopold 1968; Andersen 1970; Hammer 1972, 1973a, 1973b; Putnam 1972; and Schueler 1987):

1. Higher peak flows and increased volume of stormflow per unit of rainfall on the watershed.
2. Decreased time of concentration, particularly where extensive drainage improvements have been made; decreased time from rainfall onset to peak of stormflow.

3. Reduced baseflow, particularly during prolonged drought periods, due to reduced infiltration and soil storage.
4. Increased frequency and severity of flooding.
5. Increased stream channel erosion that enlarges the channel and causes greatly increased bank erosion rates in meanders.

Any watershed perturbation that causes significant increases in runoff will also usually result in degradation of water quality and degradation of aquatic ecosystems (Leopold 1968, Hammer 1972, Dietemann 1975, Ragan and Dietemann 1976, Klein 1979, Benke et al. 1981, and Schueler 1987). Extremely high rates of erosion from construction sites coupled with increased channel erosion result in greatly increased sediment loads in stormflows. Input of pollutants of many types is greater than from undisturbed watersheds and for certain pollutants, such as petroleum hydrocarbons and heavy metals, urban areas are worse polluters than agriculture or other land uses that involve regular land disturbance. Extremely high levels of coliform bacteria are common in urban runoff, particularly where leakage from sewer lines may directly enter storm drains or streams. The quality of habitat for all sorts of aquatic animals is degraded in streams affected by urban runoff. Increased suspended and bed load sediment directly affects vertebrates and invertebrates alike. Sediment deposits destroy habitat. Certain pollutants, particularly heavy metals and pesticides, may adversely affect aquatic animals. The net cumulative effect is a reduction in population levels and diversity of aquatic insects and other macroinvertebrates and the fish populations whose food supply and habitat has been degraded.

Urbanization thus is a process that has tremendous adverse impacts on downstream aquatic ecosystems. The changes may be readily and quickly apparent immediately downstream of a

development during the construction process when the first large storm leaves fresh erosion scars and deposits of sediment in the channel. The impacts in larger streams farther away from the source of the hydrologic changes may take longer to progress to the point of being noticed. The stream system buffers the impacts somewhat at greater distances from the location of the development and the larger, more infrequent storms are the source of much of the adverse impacts. However, the cumulative adverse changes in streamflow and water quality caused by urbanization can have far-reaching effects in stream systems that are not easily nor inexpensively ameliorated.

METHODOLOGY

General Approach

Addressing the objectives of this study involved two separate but highly correlated impacts of urbanization on stream ecosystems - water quality degradation and increased rate and volume of stormflow. The best method for determining the hydrologic impacts of land use change is the classic paired watershed study. In this approach, the hydrologic characteristics of two similar watersheds are measured for extended periods before and after treatments are applied in one of the watersheds. To determine the hydrologic impacts of changing conditions in a watershed where long-term historical data is not available, less definitive but still useful procedures must be utilized. In this case, stream ecosystem characteristics indicate that the upper section of the watershed of Poore Creek has experienced significant change in recent years while the upper section of the watershed of Harrison Creek has remained stable. The conditions in the Harrison Creek watershed can then, within limits, be used as a benchmark for comparing the conditions in the Poore Creek watershed.

The only viable option for studying the hypothesized hydrologic changes in the headwaters of the watershed of Poore Creek was the use of a runoff model to predict the stormflow hydrograph entering the battlefield under watershed conditions with a lower level of development than at present. The general approach was to calculate the stormflow hydrographs with several appropriate models using observed rainfall and then to compare the observed hydrographs to the predicted ones to select the model that provided the best predictions. The selected model was then used to calculate predicted runoff hydrographs for larger rainfall events than those observed and for different development scenarios. Stormwater detention options were also analyzed.

Using model predictions of runoff characteristics is less accurate than actual historical data on runoff. However, the models in common use for such analyses are widely used and accepted in the hydrology profession. A distinct advantage of the modeling approach is that predictions of stormflow characteristics can be made for a wide range of flows and for different development scenarios and stormwater management options can be designed and tested.

Two standard approaches were used to determine the general quality of the water in the two streams. Periodic grab samples were analyzed for concentration of suspended sediment and dissolved constituents, biological oxygen demand, turbidity, and coliform bacteria. Comparisons of the results between streams and comparison to standard water quality criteria were used to determine whether water quality in Poore Creek was significantly degraded. A study of the species richness and density of macroinvertebrates was conducted to determine the status of an ecosystem component that is highly affected by water quality. Conclusions could be drawn by comparing macroinvertebrate species richness and density values between the two streams and also to standards for similar streams with high water quality.

Determining whether significant stream channel erosion is still ongoing may require monitoring of channel characteristics for a number of years. In this study, the baseline stream channel cross-sections were established and a couple of short-term measurements were made.

Site Description

Petersburg National Battlefield is located in the middle coastal plain of Virginia where the terrain generally is gently rolling with broad interstream divides. However, where the James River and its main tributary, the Appomattox River, bisect the coastal plain from west to east, the two rivers have deeply incised channels in the erodible coastal plain sediments. The water

divide that separates the Appomattox River watershed from that of the Nottoway and Blackwater Rivers to the south (tributaries of the Chowan River) is a broad low gradient ridge (slopes less than 1%) that trends northeast to southwest. The water divide is located only about 2.7 mi from the Appomattox River in the vicinity of the battlefield. Elevations range from 155 ft on the water divide less than 1 mi south of the battlefield to about 5 ft where Poore and Harrison Creeks empty into the Appomattox River about 0.75 mi north of the battlefield. Elevations within the battlefield range from about 150 ft to 40 ft.

Poore and Harrison Creeks are two of a series of short, parallel, high gradient tributaries of the Appomattox River that are deeply incised into the terrain. The longitudinal channel gradients of the two streams average about 40 ft/mi. Topography within the battlefield is steeply rolling with steep slopes down to the two main streams. Slope gradients range from a low of about 3% on the gentler upper slopes to as high as 50% on steep slopes adjacent to the creeks. Poore and Harrison Creeks are both third order streams.

The soils of the area are dominated by deep, well-drained and moderately well-drained loamy sands and sandy loams (Jones, et al., 1985; McKinney, 1976). Moderate to high permeability is common in the deep sandy loam and loam upper layers that range up to 2 ft deep on some soil types. The substratum in the area, commonly below 4-5 ft, varies from sandy clay loam to clay and commonly has red and gray mottles, indicating relatively low permeability and long periods of saturation. That substratum, where exposed in much of the thoroughly scoured channel of Poore Creek, is a massive, plastic, low permeability material.

The combination of steep slopes, very permeable surface soils, and slightly permeable substrata results in flashy watersheds even when covered by undisturbed forest. Streamflow

responds rapidly to rainfall, rising rapidly from low baseflow to high stormflow peaks and receding just as rapidly. The short lengths and steep gradients of Poore and Harrison Creeks also contribute to the rapid recession of stormflow. Infiltrating rain water moves rapidly to the streams through the steep gradient, permeable soils, but the short travel time through a high gradient channel to the Appomattox River rapidly moves the water through the channel and out of the watershed. Stormflows of high velocity and turbulence also are highly erosive and carry high loads of suspended sediment.

Hydrologic Analyses

Rainfall Measurement

A tipping bucket rain gauge with an analog chart event recorder was used for continuous recording of rainfall. The rain gauge was located in the northwest corner of the Harrison Creek watershed near the water divide between the two watersheds. Rainfall amounts at hourly intervals were input via digitizer to spreadsheet software for use in the hydrologic analyses.

Stormflow Measurement

Measurement of streamflow from the upstream watersheds was conducted at the southern perimeter of the battlefield where the streams enter the battlefield. For both streams, the gauging stations were located at the upstream ends of concrete box culverts that carry the streams under streets that parallel the battlefield boundary. The gauging station for Harrison Creek was located on the south side of Hickory Hill Road, a City of Petersburg Street adjacent to the battlefield boundary. The gauging station for Poore Creek was located on the south side of Siege Road, a road within the battlefield that is about 300 ft north of the boundary. Stream stage in the entry of the culverts was continuously recorded in a stilling well of corrugated steel

pipe mounted to the retaining wall adjacent to the end of the culvert with the end of the connecting pipe to the well extending to the entry lip of the culvert. Stage at each station was continuously recorded with a Stevens Type F water level recorder. Breakpoints on the stormflow stage hydrographs were input to spreadsheet software via digitizer. The stage discharge relationship for each culvert was used in the spreadsheet to convert the stormflow stage hydrographs to discharge.

A stage discharge relationship was developed for each of the culverts where stormflow was measured. The engineering hydrology literature contains a number of different methods for estimating flow through culverts, depending on the characteristics of the culvert and the inlet and outlet channel sections. The culverts used for measuring stormflow in this study are under inlet control and five applicable methods were analyzed to determine the one best suited to these culverts:

(1) Standard culvert capacity charts (USDA Soil Conservation Service 1985)

(2) Culvert rating equations

- (a) culvert partially full
- (b) culvert as a weir
- (c) culvert as on orifice
- (d) Manning's equation

The standard charts could not be used because the culvert characteristics did not closely fit any in the charts. Equations 2a and 2b are not appropriate for use where headwater depths may exceed 4.5 ft, the interior height of these culverts. Equation 2c is not appropriate when headwater depth is less than 4.5 ft. Analysis of discharge estimates using Manning's equation

indicated that it overpredicted flow as compared to methods 1 and 2c when headwater depths exceed 6.5 ft, probably because the assumption of inlet control no longer holds under such high velocity conditions.

Therefore, we decided to use a combination method of two equations to ensure accurate discharge estimates at different depths. The equation for a culvert acting as a weir was used for headwater depths equal to or less than 4.5 ft and the equation for a culvert acting as an orifice was used for headwater depths of 4.5 ft or greater. The equations for this combination stage discharge relationship are:

For Hw $\leq$ 4.5 ft:

$$Q = Cw * B * (Hw)^{1.5}$$

For Hw > 4.5 ft:

$$Q = Cd * B * D\ [64.4(Hw - D/2)]^{0.5}$$

where Q = discharge, cubic feet per second (cfs)

Cw = coefficient for a broad-crested weir = 3.0

B = Width of culvert, feet

Hw = head water depth (stage), feet

Cd = coefficient for an orifice = 0.59

D = height of culvert, feet

Runoff Modeling

Determining the impact of recent upstream development on the stormflow characteristics of Poore Creek, predicting the hydrologic impacts of future development on both streams, and testing options to reduce peak rates of stormflow involved a series of procedures:

(1) Selecting observed storm events and generating design storms for use in model testing and stormflow predictions; choosing watershed development scenarios for use in model predictions.

(2) Calculating the runoff hydrographs with two standard models using observed rainfall amounts to determine the model that provides the best predictions of stormflow characteristics when compared to observed runoff hydrographs.

(3) Using the selected model to predict the character of stormflow hydrographs for the two streams for design storms of return periods larger than those in the observed data set.

(4) Using the selected model to predict the character of stormflow hydrographs for scenarios with different levels of watershed development.

(5) Calculating the peak discharge rates using observed rainfall amounts with five methods that are commonly used to provide rapid, simplified estimates of peak flow for design of stormwater management structures.

(6) Using the model and the 10-year return period design storm to calculate detention basin storage volumes for various peak flow control options.

Since it is the larger stormflow events that most affect stream channel morphology, the largest events were chosen from the 2.5 year record of runoff for which reliable data on rainfall and streamflow were available for the duration of the entire rainfall runoff event. Four storm events were selected for Harrison Creek and five storm events for Poore Creek, three of which were common to both creeks. Peak flow rates for the selected events ranged from 23.5 to 116.0 $ft^3/sec/mi^2$ in Harrison Creek and from 28.2 to 216.9 $ft^3/sec/mi^2$ in Poore Creek. None of these

rainfall events were larger than the 2-year return period event but still represent the periodic larger events that influence channel characteristics.

The design storm is a hypothetical rainfall event that is used in stormflow prediction models to predict the stormflow hydrograph for a rainfall event of a specified duration, size, and distribution of rainfall intensities over the time period of the event (Bedient and Huber 1988). The stormflow prediction models used in this study require 24-hour duration events. Event size (i.e. total rainfall amount) is characterized by return period, the average long-term recurrence interval for events of a specified duration. The rainfall depths for the specified recurrence intervals for this study were taken from charts in Frederick, et al. 1977. (Appendix Tables 11 and 12). The distribution functions of rainfall intensity vs. time in the event are average region-wide distributions developed by the Soil Conservation Service from historical rainfall data (USDA Soil Conservation Service 1985, 1986). The Type II distribution was used for the analyses in this study. The design storms selected were the 10, 25, 50, and 100 year 24-hour events. Those events represent the long term average rainfall depth and intensity distribution for events of 24 hours duration that occur on the average every 10, 25, 50, or 100 years.

In the models employed for this study the factor that is used to characterize the impact of degree of suburban and urban development in a watershed is the percent of impervious area. Model calculations were used to compare stormflow characteristics under existing conditions to that for historically lower levels of development and to predict how stormflow characteristics will change as increased development occurs. Such scenarios were also used in the analysis of detention pond storage requirements. Standards in the literature (McCuen 1989) were used for the percent impervious area for different types of suburban and urban land uses. For example,

commercial or business areas average about 85% of the area in impervious surface; paved streets, parking lots, roofs, etc. have about 98% imperious area; and residential areas with 1/4 acre lots have 38% impervious area. The area in the watersheds in the various land uses was used to compute the net percent of impervious area (Appendix Tables 1-6). Existing conditions in the Harrison Creek watershed were 13.5% impervious area and in the Poore Creek watershed were 28.0% impervious area. The existing land use distributions were then proportionalized to provide hypothetical development scenarios such that:

(1) Stormflow in Poore Creek could be predicted at the same level of development that existed in the Harrison Creek watershed (13.5% impervious area), (2) Stormflow from Harrison Creek could be predicted at the higher level of development that existed in the Poore Creek watershed (28.0% impervious area) and, (3) Stormflow in Poore Creek could be predicted for a level of development higher than that which existed at the time (42.5% impervious area). The 24-hour 10-year recurrence interval event was used in calculating predicted stormflow hydrographs and calculating detention pond storage requirements because it is the standard event used in engineering design of stormwater management systems.

Several different simulation and predictive models that are applicable to predicting the character of stormflow for small watersheds were tested for use in this study. The Soil Conservation Service TR-55 Tabular Hydrograph (tabular hydrograph) Method (USDA Soil Conservation Service 1985, 1986) and the U.S. Army Corps of Engineers HEC-1 SCS Loss Function (HEC-1) Method (U.S. Army Corps of Engineers, 1986) were applied for simulating runoff hydrographs for selected storm events (Procedure 2). Predicting hydrographs for design storms and for different levels of development was accomplished with HEC-1 (Procedures 3 and

4). Models based on the tabular hydrograph method; the HEC-1 method; the SCS Graphical Peak Discharge (graphical peak discharge) Method; and the rational formula (Bedient and Huber 1988, McCuen 1989), a simple calculation of peak discharge per square mile per inch of runoff, were applied for computing peak discharge (Procedure 5). The storage pond option included in the SCS modeling package was used to calculate the detention pond storage needed for different peak flow control scenarios (Procedure 6).

The principal input parameters for the models were on-site 24 hour rainfall amounts for the selected storms, maximum 24-hour rainfall amounts for specific design storms (10, 25, 50, and 100 year return periods) and various physical parameters of the watersheds. On-site rainfall was measured as described above. Maximum 24-hour rainfall data for the region for the four return periods selected for model predictions were obtained from U.S. Weather Bureau rainfall analyses (Hershfield 1961, Frederick et al. 1977). Information on soils, land use, and physical characteristics of the watersheds were obtained from soils maps, U.S. Geological Survey 7.5 minute series quadrangles (Prince George and Petersburg quads, photo revised, 1981) and aerial photographs (1982, scale 1:7792) obtained from the Virginia Department of Transportation. Watershed boundaries and other critical parameters were checked on site where necessary. Estimated parameters such as runoff curve number, time of concentration, travel time, runoff coefficient, lag time, etc. were determined using sources and procedures detailed in the model handbooks. Watershed parameters are listed in Appendix Tables 1-10.

1. SCS Tabular Hydrograph Method

The tabular hydrograph method provides simplified procedures to calculate storm runoff volume, peak rate of discharge, runoff hydrographs, and storage volumes required for flood

water detention purposes. The procedures were developed for small watersheds with a variety of land uses and are applicable, especially, to small urbanizing watersheds. The model assumes as primary input the rainfall amount uniformly imposed on the watershed over a specific time distribution. Mass rainfall is converted to mass runoff by using the runoff curve number (CN) method. The CN is an index based on soils, plant cover, amount of impervious area, interception, and surface storage that integrates all the basic factors that influence storm runoff. Runoff is then transferred into a hydrograph by using the SCS unit hydrograph approach and routing procedures that are based on estimates of runoff travel times through segments of the watershed.

Input parameters for the tabular hydrograph method were determined as follows:

(1) Using the USGS quadrangles, each watershed was divided into subareas (subwatersheds) that were relatively homogeneous and the area of each was determined. The Poore Creek watershed was divided into 5 subareas and 4 were delineated in the Harrison Creek watershed (Figure 1, Appendix Tables 1 and 4).

(2) The 24-hour total rainfall for the selected storm events was obtained from the rainfall dataset and the appropriate rainfall distribution was selected (Type II).

(3) The CN was determined for each subarea (Appendix Tables 1-5) from tables in the manual (USDA Soil Conservation Service 1985, 1986).

In order to compute the average subarea curve numbers, the different land uses such as residential areas, wooded areas, open space, roads/highways, commercial areas etc. were delineated on the aerial photos. Then the areas (Ai) of each of the different types of land uses were determined. For each hydrologic soil group and land use complex, the specific curve

number (CNi) was determined from the curve number charts. Using Ai and CNi for each type of land use (i) prevailing on each subarea, a weighted average curve number (CN) was estimated for each subarea as:

Area weighting not approp.

$$CN = \Sigma(Ai*CNi)/\Sigma Ai$$

(4) The time of concentration (Tc) (Appendix Tables 6-10) for each subarea was calculated as a function of lag time (L):

$$Tc = 1.67L \qquad L = \frac{Z^{0.8}\ (S+1)^{0.7}}{1900y^{0.5}}$$

in which:

L = lag time, hours

Z = hydraulic length of subarea, feet

S = potential storage = $\dfrac{1000}{CN} - 10$

CN = curve number for the hydrologic soil-cover complex

Y = average subarea slope = $\dfrac{\textit{subarea relief}}{\textit{hydraulic length}}$

Subarea relief is the difference in elevation between the mouth and the highest point on the perimeter and hydraulic length is the distance from the mouth to the most remote point on the perimeter.

(5) Travel times (Tt) were computed as the uniform flow velocity at bankfull conditions divided by the reach length.

In the model, the effective rainfall or net storm runoff from the watershed is computed using the equation:

$$Q = \frac{P-(0.2*S^2)}{P + 0.8S}$$

in which: P = 24-hour rainfall, inches

S = potential storage

2. U.S. Army Corps of Engineers HEC-1 Model

HEC-1 is a large, complex, sometimes cumbersome model that is widely accepted for modeling the rainfall-runoff process. It offers many options for hydrograph formulation and channel routing and is in that sense, very flexible. HEC-1 although developed for large basins, also is applicable for watersheds of all sizes. The HEC-1 SCS dimensionless unit hydrograph approach was used to model the Poore and Harrison Creek watersheds because it is applicable to small watersheds (<2000 acres). Most of the same input data and information required for the tabular hydrograph method are also needed for modeling by this process. Additional parameters are:

(1) The bedslope of the stream elements was measured from the USGS quadrangles as

$$S = \frac{L}{Z}$$

in which: L = length of stream element, feet

Z = difference in elevation at the ends of the stream element, feet

(2) A Manning's roughness coefficient of n = 0.085 was assumed for unmanaged channels with brush (McCuen, 1989).

(3) The channel sections were assumed roughly as trapezoidal with side slopes 2.1:1 and a bottom width of 7 ft (approximately) for Poore Creek and side slopes 1:1 and a bottom width of 4.6 ft (approximately) for Harrison Creek based on average cross-sections surveyed.

(4) Hourly incremental precipitation for the observed storm events was obtained from the rainfall data set.

(5) Cumulative precipitation depths (inches) at 5, 10, and 30 minutes and 1, 2, 3, 6, 12, and 24 hours duration were used for the hypothetical design storms for return periods of 10, 25, 50, and 100 years. For channel routing, kinematic wave routing was used because it causes little peak attenuation, a characteristic of many urban and urbanizing watersheds.

3. Peak Discharge

Calculations of peak discharge for storms of return periods of 10, 25, 50 and 100 years were conducted using the tabular hydrograph method; the HEC-1 model; the graphical peak discharge method; and the rational formula, which is a simple calculation of peak discharge per square mile per inch of runoff. Input parameters were the same as those described above. The graphical peak discharge method provides a determination of peak discharge only for a hydrologically homogeneous watershed with soils, landuse, and cover distributed uniformly. The method is generally useful for developing quick estimates of peak discharge for both

undeveloped and developed conditions of a watershed. These outputs can later be used for estimating the storage volumes needed for providing detention ponds to control peak outflow downstream of the watershed due to upstream developed conditions. The rational formula is an old and widely used equation that is useful for estimating point peak discharge from urbanizing or urban watersheds of relatively small size. The equation is:

$$Qp = CIA$$

in which: C = composite runoff coefficient; weighted average of runoff coefficients for the different land use types in the watershed.

A = area of the watershed, square miles

I = intensity of rainfall (in/hr) for a duration equivalent to the time of concentration for the whole watershed.

The runoff coefficient is an index for different land uses similar in concept to curve number (McCuen, 1989). The time of concentration in this model was estimated using the Kirpich Equation

$$Tc = \frac{(L^3/H)^{0.385}}{128}$$

in which: Tc = time of concentration, minutes

L = hydraulic length of the watershed, feet

H = watershed relief, feet

Model parameters are listed in Appendix Table 13.

4. Detention Basin Storage Analysis

The detention storage option available in the SCS package of models that includes the tabular hydrograph and graphical peak discharge methods was used to estimate the volume of storage capacity needed to control the outflow peak discharge from the Poore Creek watershed to that predicted for 13.5% impervious area (USDA Soil Conservation Service 1986). The input requirements for the model were the detention basin inflow peak and volume for 28% impervious area (qi) and the desired outflow peak for 13.5% impervious area (qo). The model compares the qo/qi ratio, the resultant ratio of storage volume to inflow volume Vs/Vr and the volume of detention basin storage (Vs) needed for the particular design storm (10-year, 24-hour rainfall).

Water Quality

Suspended and Dissolved Constituents

Grab samples were collected from the two streams on a weekly to biweekly schedule by National Park Service personnel at two locations on each stream. Samples were collected at the downstream ends of the culverts where stream stage was measured to represent the quality of the water entering the battlefield segments of the streams (upstream samples). Samples were also collected downstream near the northern boundary of the battlefield to represent the quality of the water exiting the battlefield (downstream samples). Water samples were analyzed for total dissolved solids (TDS), total suspended solids (TSS), biological oxygen demand (BOD), turbidity, and fecal coliform. When excessively high fecal coliform levels were detected in Poore Creek, a few water samples were also collected from tributaries in order to determine if a specific tributary was contributing water high in coliform. Samples were transported

immediately after collection to the Virginia Water Control Board laboratory located in Richmond, Virginia, where the analyses were conducted.

Macroinvertebrate Analysis

Benthic macroinvertebrates, or animals dwelling on the stream substrate, are often used as indicators of water quality for a variety of reasons. In particular, they are sensitive at both the individual and community level to both toxins and organic wastes. While chemical studies generally do not integrate possible water quality fluctuations between sampling periods, macroinvertebrates, with relatively long life cycles, reflect both long- and short-term water quality conditions. Also, these organisms tend to integrate and monitor the effects of the entire array of potential pollutants at a site, including both synergistic and antagonistic effects that chemical monitoring studies can not normally predict. These attributes make them excellent indicators of water quality.

The general approach for the sampling program was to incorporate both quantitative and qualitative sampling in both streams during two sampling periods. Sampling was conducted on February 4 and April 22, 1987, encompassing the time of year when macroinvertebrate densities and especially diversity are near their maximum.

Two sites on each stream were sampled during both sampling periods. The upstream sampling station on Harrison Creek (designated as H-1) was located just upstream of the Park boundary across Route 460. The second sampling site (H-2) was located immediately upstream of the location where the stream crosses the main Park road. Poore Creek was sampled near the Crater Parking Lot (P-1) and again farther downstream near the Fort Haskell turnout (P-2).

Quantitative samples were taken using Hess stream bottom sampler (0.088 m^2) with a

0.35 mm pore size mesh net. This pore size effectively sets the minimum size of organisms that could be collected during sampling. Five Hess samples were taken at each of the four sampling site during each of the two sampling periods. Each set of five samples was taken at midstream over approximately a 20 m length of stream.

Samples were preserved in 70% isopropyl alcohol with Rose Bengal stain added to aid in sorting the organisms. In the laboratory, organisms were removed from the associated debris in each sample under a dissecting microscope, identified to the lowest taxon possible, and enumerated on per meter-squared basis. Chironomidae (Insecta: Diptera) were mounted on glass slides with polyvinyl lactophenol and identified under a compound microscope.

Qualitative sampling of the macroinvertebrates was conducted using a dip net. The objective of this sampling was to collect in habitats not sampled with the Hess sampler, for example on wood and collections of leaves in the water. These samples provided a more complete list of species inhabiting the streams.

Data analysis included an examination of the species list from each stream for indicator organisms, or species whose presence or absence indicate either high or degraded water quality. In addition, the data at each site were examined in terms of species richness (the total number of species present in a stream), densities (mean number of individuals per m^2), and diversity (Shannon Weiner Index). Increases in water quality generally correspond to increasing species richness and diversity; densities to some degree reflect the level of production in a stream, with very low or very high densities suggesting a deviation from natural water quality.

Stream Channel Cross-Sections

The channels of both streams within the battlefield were surveyed in the summer of 1986

to provide a baseline for long-term monitoring of changes in the elevation of the floodplain, the general course of the channel, and the geometry of the channel. A level traverse was surveyed along both channels on the western sides with stations adjacent to the channel at the top of the bank. Cross-section geometry was determined by establishing permanent cross-section stations at 16 locations along Harrison Creek and 14 locations along Poore Creek. At each station a level line was strung across the channel from points on the trunks of large trees. The vertical distance to the top of the bank and the surfaces of the sides and bottom of the channel were measured at 1 ft intervals along the level line. Measurements of the cross-sections were made in June, 1986, February, 1987, and February 1988.

RESULTS AND DISCUSSION

Hydrology

Observed Events

Precipitation was somewhat below the annual normal (long-term average, 1951-1980) during the three years encompassed by this study. The annual normal for the station at Hopewell, Virginia is 44.8 in (National Oceanic and Atmospheric Administration 1984). In terms of monthly normals, rainfall is relatively well distributed throughout the year with monthly normals during fall, winter, and spring ranging from 3-4 in and during July-September ranging from 4-5 in. Annual precipitation amounts at the battlefield rain gauge were 30.95 in, 49.95 in, and 27.02 in respectively for 1986, 1987, and 1988 (Figures 1-3). Unusually low rainfall occurred in 1986, the first year of the study, with every month except August and December being well below normal and June being near a record low. The monthly variation in 1986 was extremely atypical because months with rainfall less than 1 in or more than 7 in are extremely rare in the Hopewell record. While still below normal, the rainfall in 1987 was reasonably well distributed throughout the year. Rainfall was again well below normal in 1988, particularly so during the first sixth months of the year that was the last 6 months of runoff measurement for the study. The net effect of those many months of drought during the period of runoff measurement for the study was a very low number of rainfall events that produced significant stormflow. Even the months of high total rainfall did not include any individual events with unusually high rainfall amounts. The six large runoff events that were selected from the stormflow data set for modeling purposes all had rainfall amounts that ranged from 1.81 to 3.01 in but were less than the 2-year return period event (Table 1).

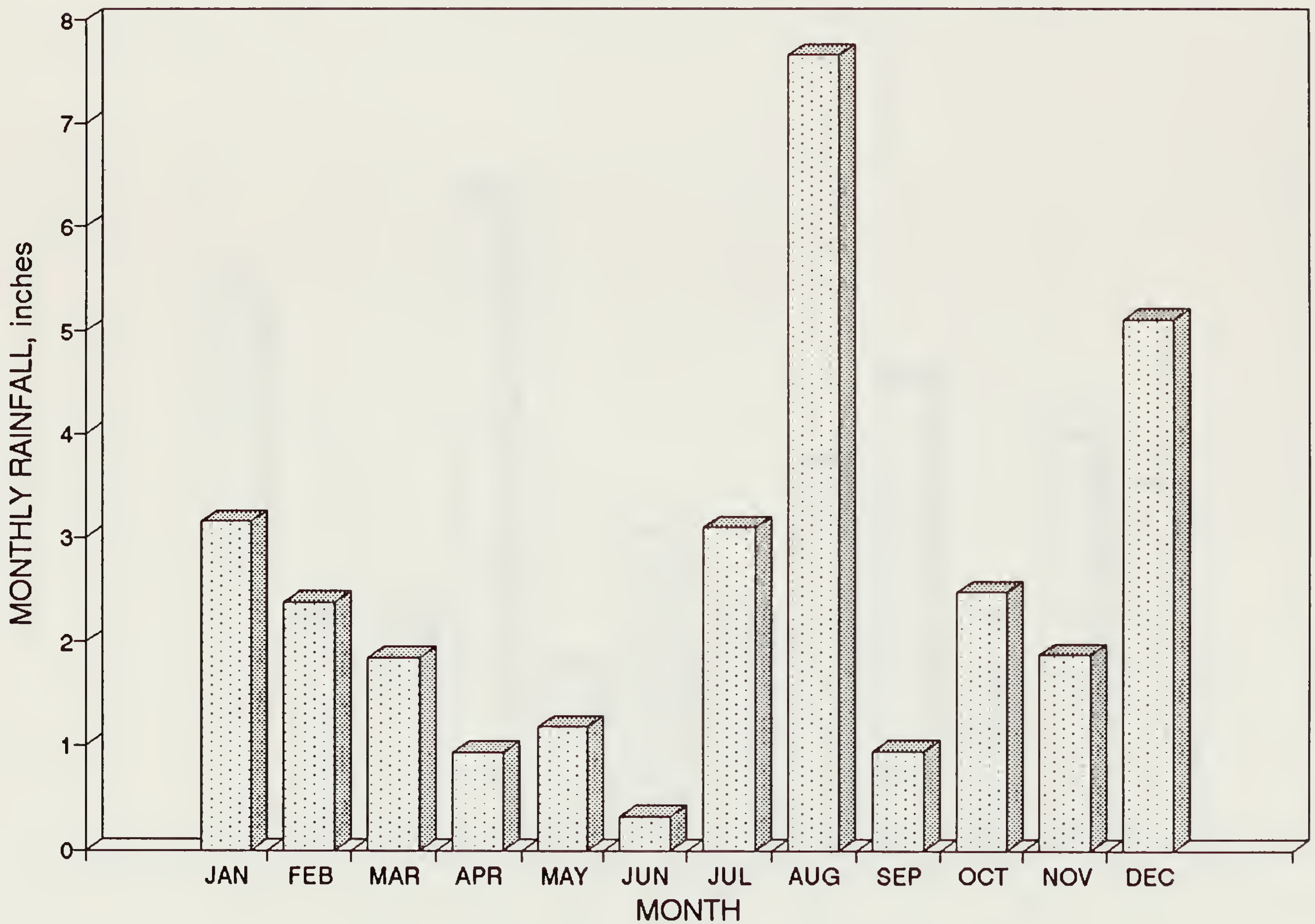

Fig. 1 Monthly rainfall for 1986 - Petersburg National Battlefield

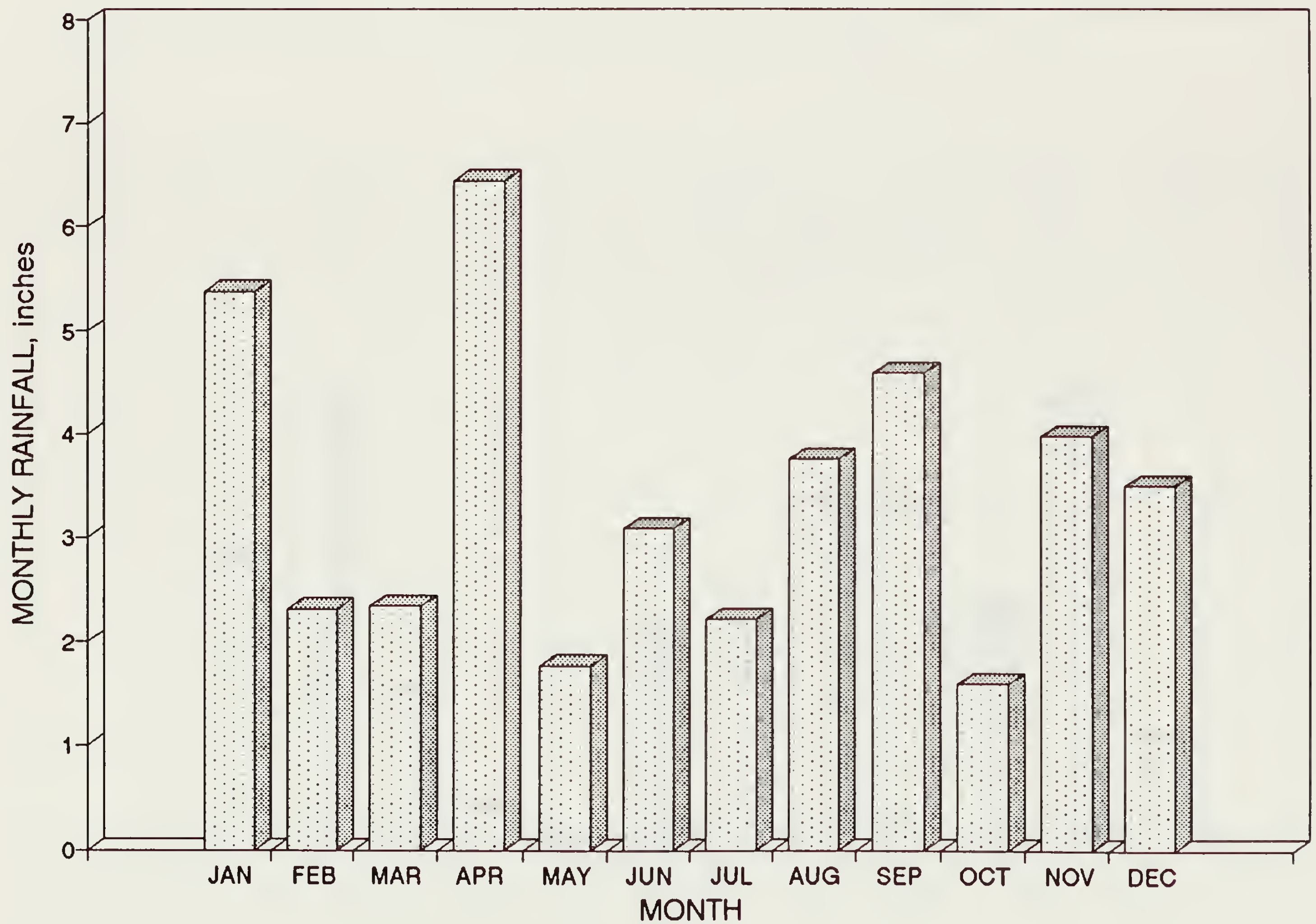

Fig. 2 Monthly rainfall for 1987 - Petersburg National Battlefield

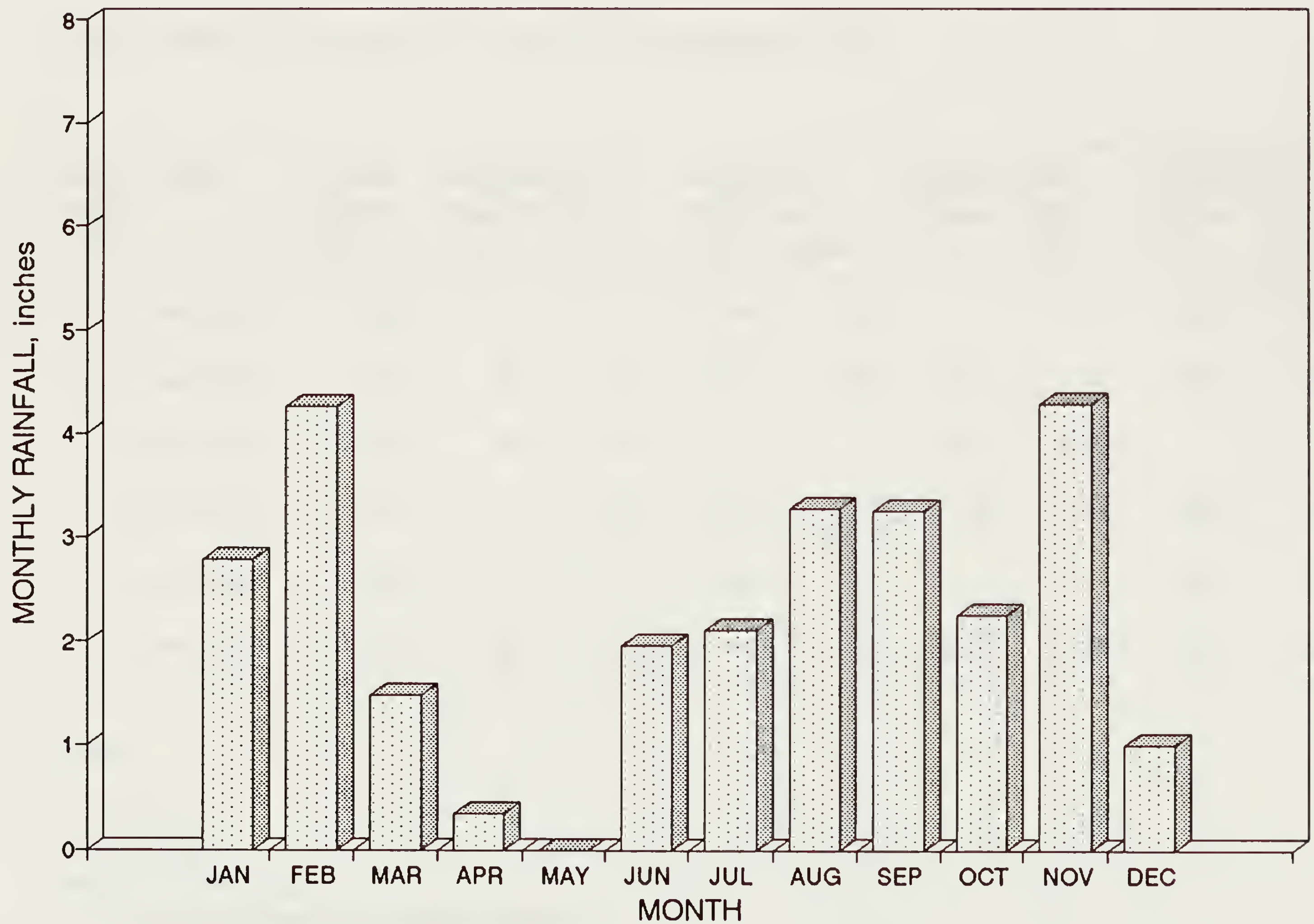

Fig. 3 Monthly rainfall for 1988 - Petersburg National Battlefield

Table 1. Rainfall and stormflow for events selected for model testing

Storm Event No.	Date	24-hour Rainfall in	Harrison Creek Peak Flow cfs	Harrison Creek Peak Flow cfsm	Poore Creek Peak Flow cfs	Poore Creek Peak Flow cfsm	Harrison Creek Volume in	Harrison Creek RF in/in	Poore Creek Volume in	Poore Creek RF in/in
1	Aug 12,86	2.50			86	84			0.35	0.14
2	Dec 24,86	2.87	28	41	126	123	0.33	0.11	0.82	0.29
3	Jan 19,87	2.04	49	72			0.79	0.39		
4	Apr 16,87	3.01	79	116	223	217	1.10	0.37	1.65	0.55
5	Sep 05,87	1.91			29	28			0.17	0.09
6	Feb 11,88	1.81	16	24	50	49	0.25	0.14	0.41	0.23

Notes:

in = inches
cfs = cu.ft./sec.
cfsm = cu.ft./sec./sq.mi.
RF = Response Factor = rainfall/stormflow

The stormflow generated by the selected events dramatically illustrates the hydrologic differences between the watersheds for Harrison and Poore Creeks. Expressing the peak rate of stormflow (peak flow) on a watershed area basis as $ft^3/sec/mi^2$ (cfsm) allows a direct comparison of the runoff rate per unit area for watersheds of different sizes (Table 1). The three large storms for which reliable data was available for both watersheds show that the Poore Creek watershed produced greater peak flow per unit area than did Harrison Creek. Peak flow per unit area (cfsm) for the event of December 24, 1986, was three times greater in Poore Creek than in Harrison Creek and was about two times greater for the other two storms. Poore Creek was more responsive to rainfall in terms of greater peak flow, but the time to peak (time from initial hydrograph rise to the maximum) was similar for the two streams. That pattern indicates that some water is being delivered to the channel rather quickly in the Harrison Creek watershed but not nearly as much (as a fraction of rainfall) as in the Poore Creek watershed (Figures 4-9). Note also the rapid hydrograph rise to a sharp peak and equally rapid recession rate in Poore Creek compared to lower rates of rise and recession in Harrison Creek.

Expressing the total stormflow volume as inches (area depth) also provides an area independent volume unit for comparing runoff from watersheds as well as comparing runoff to rainfall. The volume of stormflow in inches from Poore Creek was 1.5 to 2.5 times greater than that from Harrison Creek for each of the three common storm events (Table 1). More stormflow per unit of rainfall was produced from Poore Creek than from Harrison Creek. The mean response factors (volume of stormflow as a fraction of the volume of rainfall) for the three common storms was 0.21 for Harrison Creek and 0.36 for Poore Creek. The response factors are also indicative of the impact that antecedent soil moisture has on stormflow. The storm of

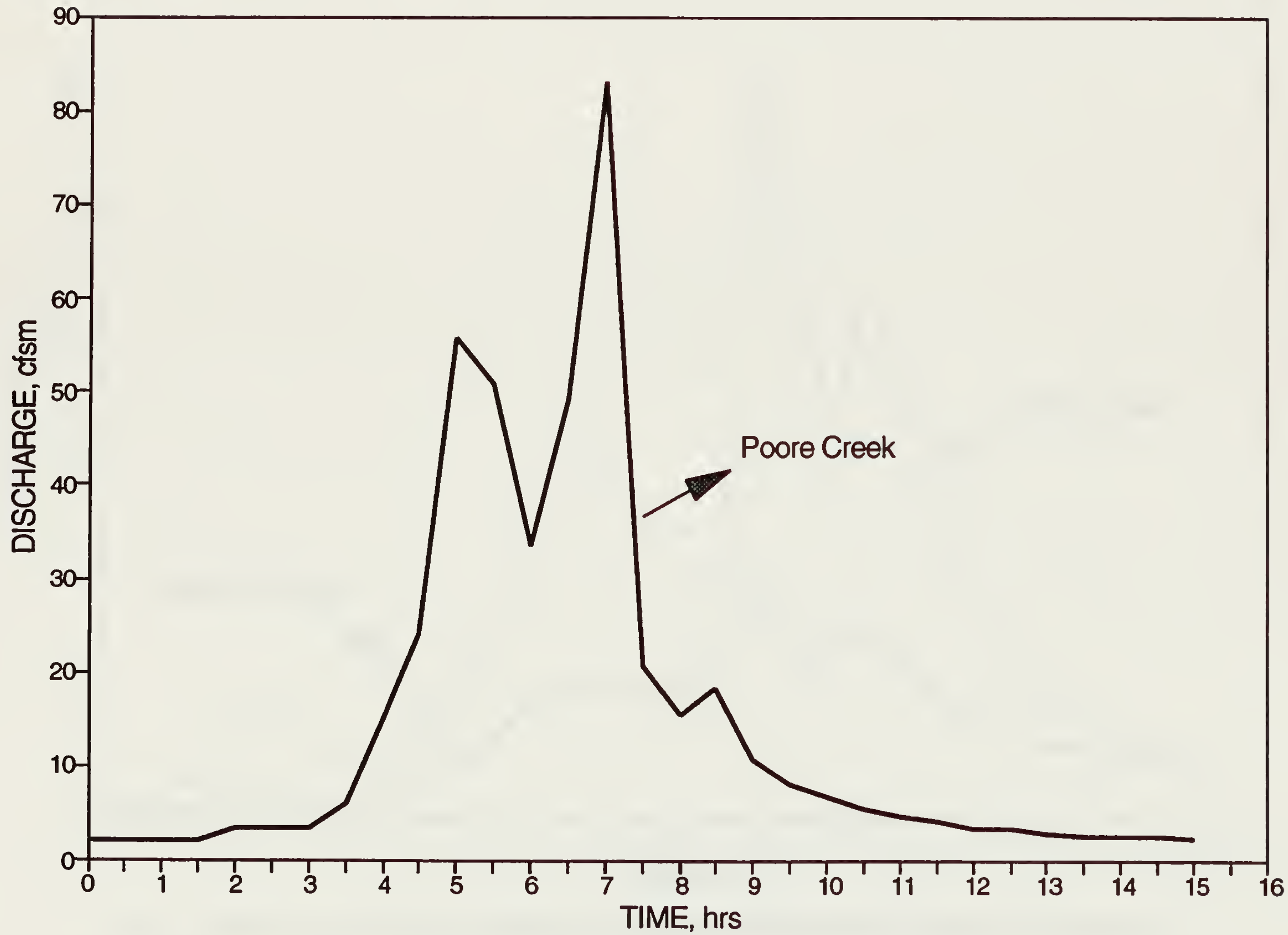

Fig. 4 Observed stormflow hydrograph for Poore Creek for event no. 1, August 12, 1986

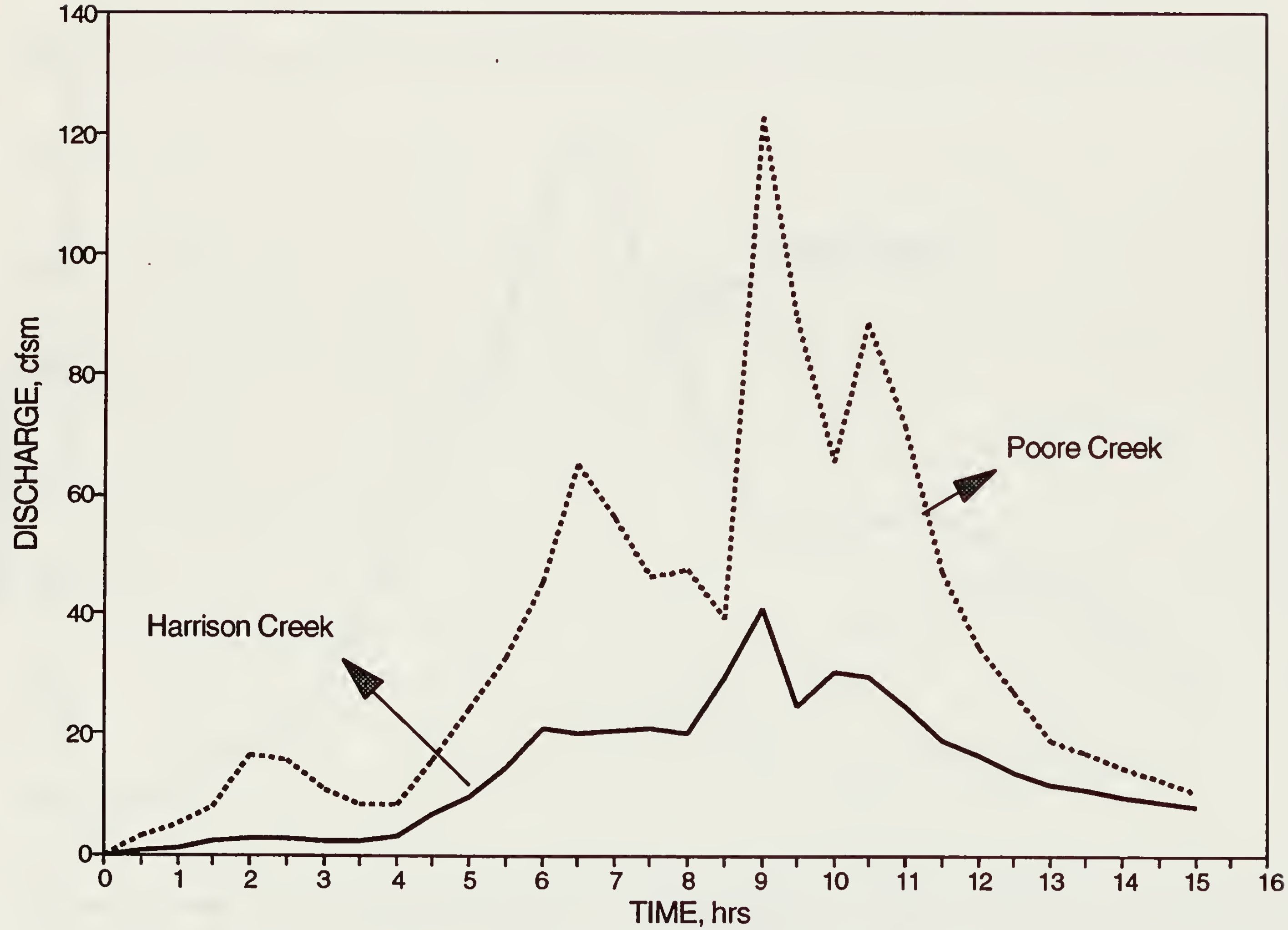

Fig. 5 Observed stormflow hydrographs for Poore and Harrison Creeks for event no. 2, December 23, 1986

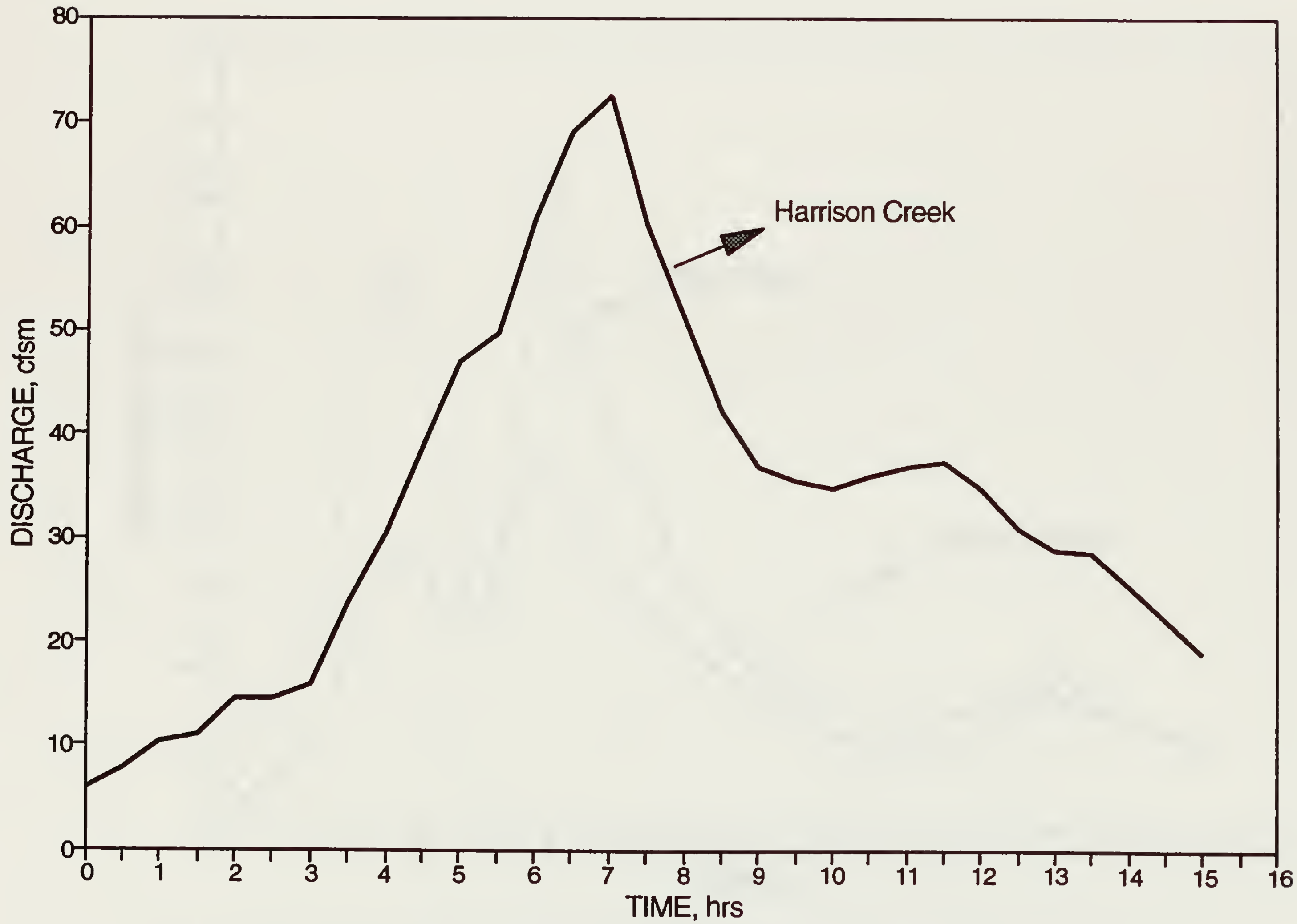

Fig. 6 Observed stormflow hydrograph for Harrison Creek for event no. 3, January 19, 1987

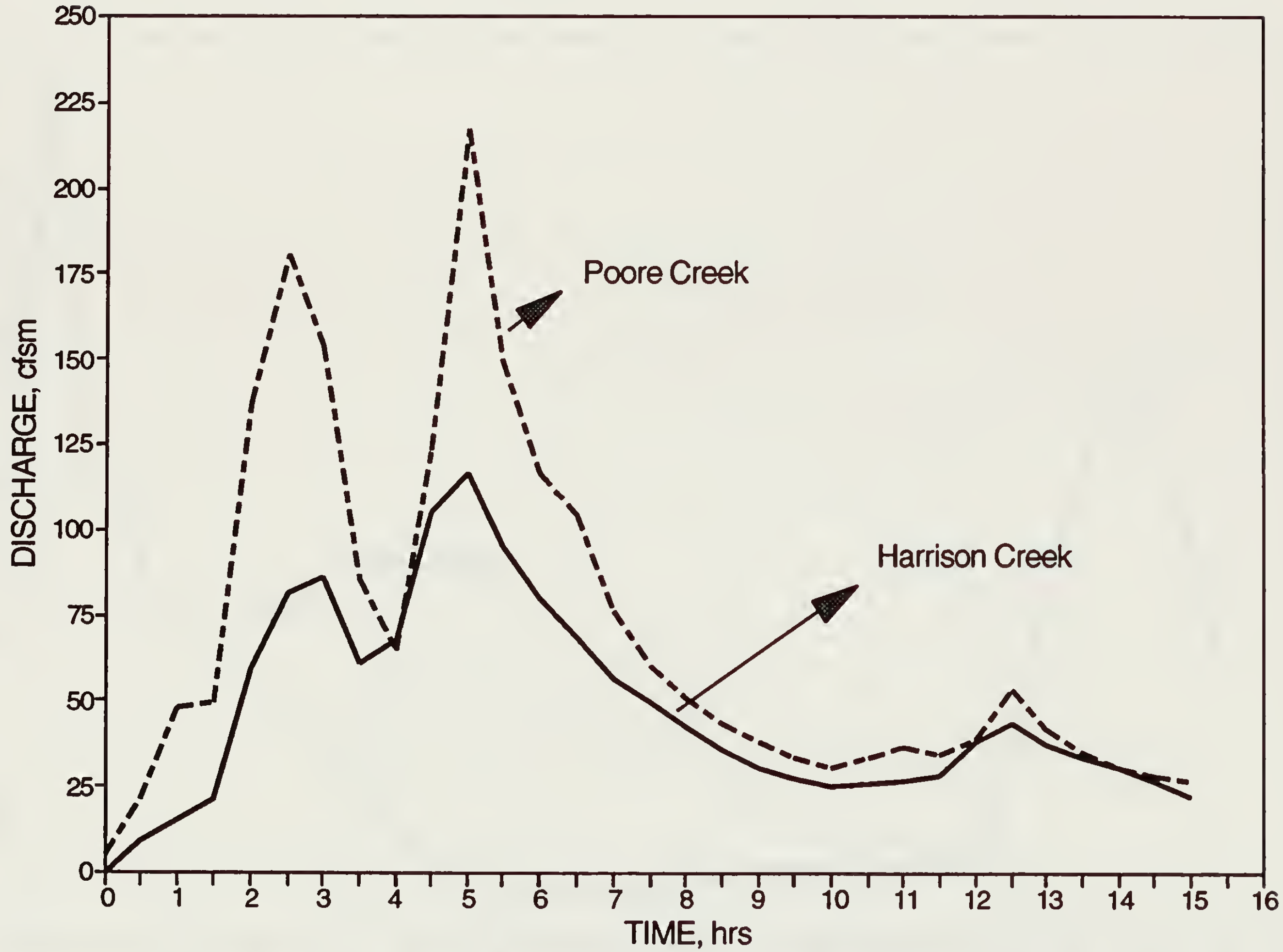

Fig. 7 Observed stormflow hydrographs for Poore and Harrison Creeks for event no. 4, April 16, 1987

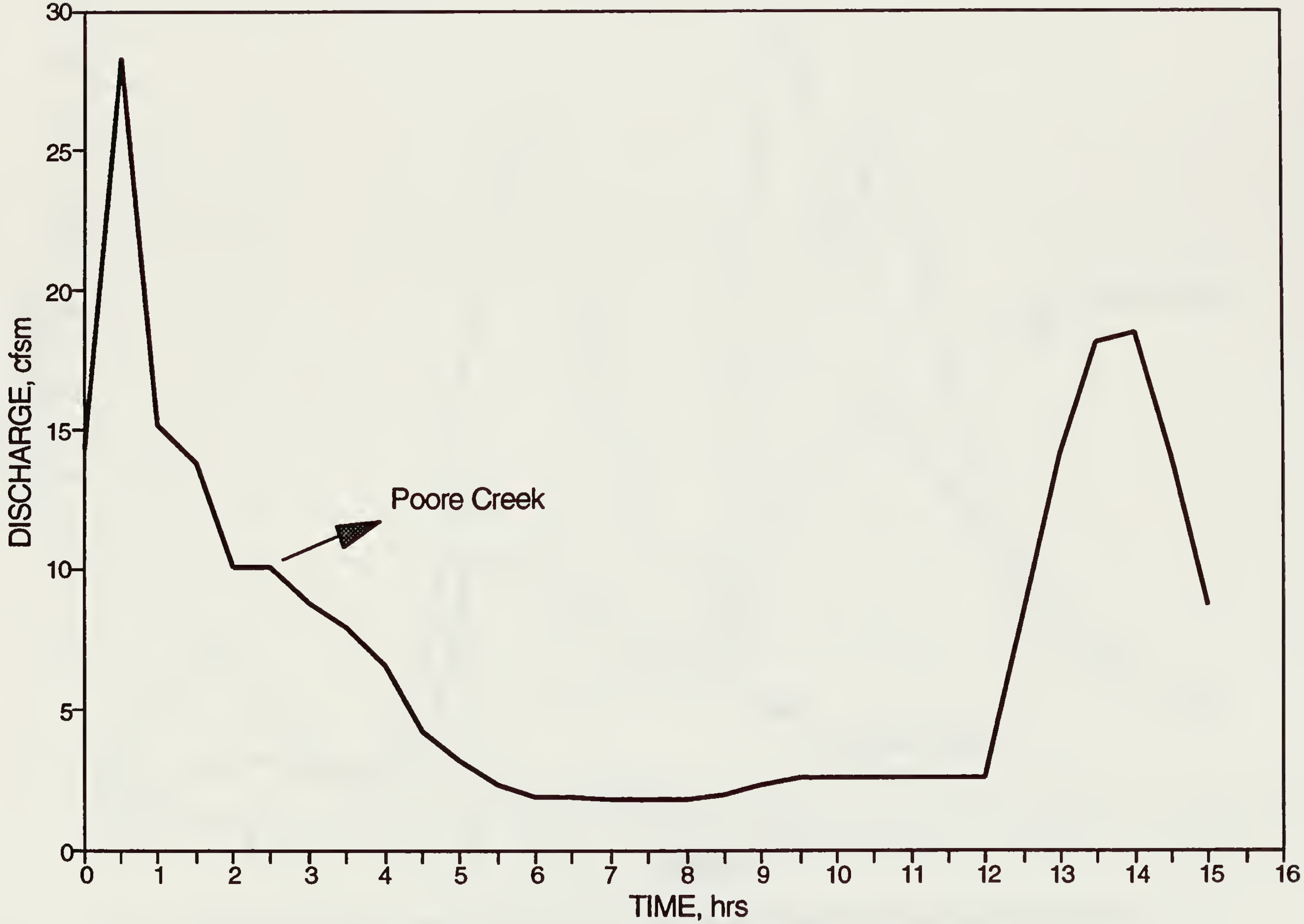

Fig. 8 Observed stormflow hydrograph for Poore Creek for event no. 5, September 05, 1987

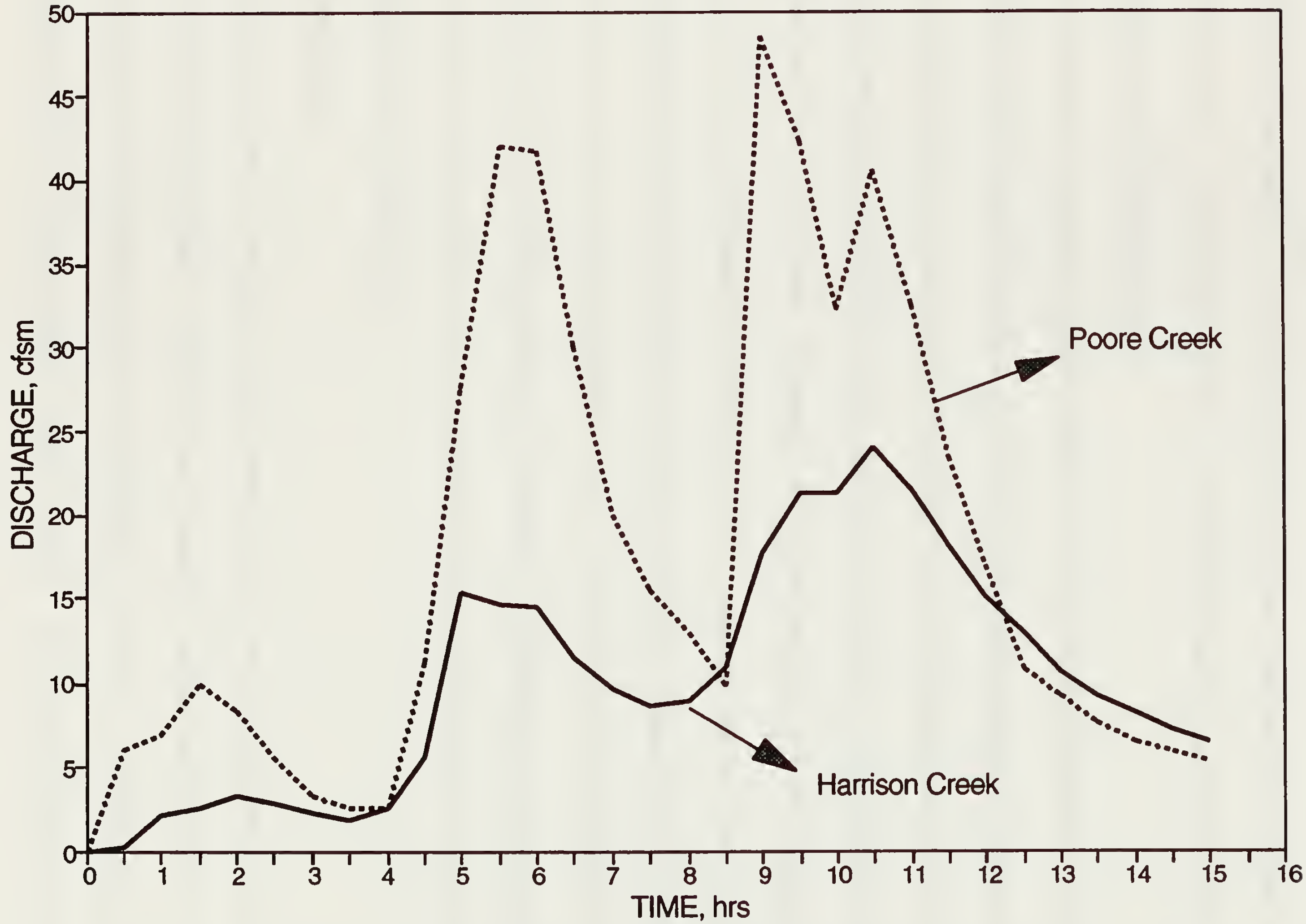

Fig. 9 Observed stormflow hydrographs for Poore and Harrison Creeks for event no. 6, February 11, 1988

April 16, 1987 was preceded by 0.89 in of rain on April 15 whereas the storms of December 24, 1986 and February 11, 1988 were preceded by 13 and 7 rainfree days respectively. The much smaller amount of available soil storage for the event of April 16, 1987 is reflected in much higher response factors than for the other two storms. Because of the higher percent of impervious surface in Poore Creek, however, the difference among the response factors is not nearly so great as for Harrison Creek.

The differences in stormflow peaks, volumes, and response factors between Harrison and Poore Creeks clearly illustrate that there are hydrologic differences between the two watersheds but firm conclusions about the factors that contribute to those differences cannot be drawn from such simple comparisons. The Poore Creek watershed at 658 acres is considerably larger than that of Harrison Creek at 436 acres. Expressing stormflow on a unit area basis helps to obviate the impact of the area differences, but differences in the shape of the main watershed, shapes and sizes of the sub watersheds, number and lengths of tributaries, watershed relief, distribution of soil types, and land use and vegetation types all contribute to the observed hydrologic differences. Thus, the modeling approach was required to specifically examine the impact of land use on the stormflow regimes of the watersheds and to analyze stormflow control options for different levels of development.

Model Predictions

Stormflows for the six historical rainfall events (Table 1) were modeled with the combined SCS TR-55 tabular hydrograph - graphical peak discharge method and the HEC-1 method. Those simulations provided predictions for peak discharge, stormflow, and the hydrograph shape for comparison with the historical events (Tables 2 and 3). For all events, HEC-1 provided a

Table 2. Peak discharges of historical storms predicted by HEC-1 & SCS models

Watershed Name	Storm Event No.	Storm Event Date	Total 24-hr rainfall	5-day antecedent rainfall	Observed Peak Discharge	Predicted Peak Discharge by		
						SCS Tabular Hydrograph	SCS Graphical Pk Disch.	HEC-1 SCS Loss Function
			in	in	cfs	cfs	cfs	cfs
POORE CREEK	1	Aug 12, 86	2.50	0.71	86	304	234	192
	2	Dec 24, 86	2.87	0.00	126	397	307	149
	4	Apr 16, 87	3.01	0.89	223	429	333	177
	5	Sep 05, 87	1.91	0.00	29	175	133	37
	6	Feb 11, 88	1.81	0.00	50	153	117	83
HARRISON CREEK	2	Dec 24, 86	2.87	0.00	28	169	137	78
	3	Jan 19, 87	2.04	1.15	49	75	59	32
	4	Apr 16, 87	3.01	0.89	79	186	151	96
	6	Feb 11, 88	1.81	0.00	16	56	43	40

Table 3. Stormflow volumes of historical storms predicted by HEC-1 & SCS models

Storm Event No.	Storm Date	Stormflow Volumes Poore Creek watershed			Stormflow Volumes Harrison Creek watershed		
		Observed in	SCS in	HEC-1 in	Observed in	SCS in	HEC-1 in
1	Aug 12, 86	0.35	1.19	0.92			
2	Dec 24, 86	0.82	1.50	1.08	0.33	1.17	0.93
3	Jan 19, 87				0.79	0.55	0.49
4	Apr 16, 87	1.65	1.32	1.35	1.10	1.31	1.10
5	Sep 05, 87	0.17	0.69	0.25			
6	Feb 11, 88	0.41	0.52	0.43	0.25	0.42	0.30

much better prediction of peak discharge than did the SCS methods with one exception. For the storm of January 19, 1987, the prediction of peak discharge in Harrison Creek by the graphical peak discharge method was more accurate than for the other two methods (Table 2). Similarly predictions of stormflow volumes by HEC-1 were much more accurate than by the SCS tabular hydrograph method except for the January 19, 1987 stormflow in Harrison Creek.

The HEC-1 method also provided more accurate predictions of the actual hydrograph shape than did the tabular hydrograph method. Comparisons of observed stormflow hydrographs with those predicted by the two methods are shown in Figures 11-14 for the storm of April 16, 1987. The HEC-1 simulations for both streams were much better predictions of the general shapes of the hydrographs as well as their peak discharge, time to peak, and total volume than were the SCS tabular hydrograph predictions. Based on these results, we chose the HEC-1 model for additional predictions of stormflow regimes under conditions different than those for the historical events.

Comparing the hydrographs predicted by the two different models illustrates the importance of selecting the best model for the specific objectives of a hydrologic study. The tabular hydrograph method, as the name implies, was originally developed by SCS hydrologists in the early 1970's as a rapid simple combination of equations and tables with limited parameter inputs. The method was intended to provide the rough estimates of stormflows from small agricultural watersheds needed for designing drainageways, detention basins, culverts, and other water management structures for agriculture. The method is also applicable to designing stormwater management structures for small urban watersheds. Since the microcomputer software to

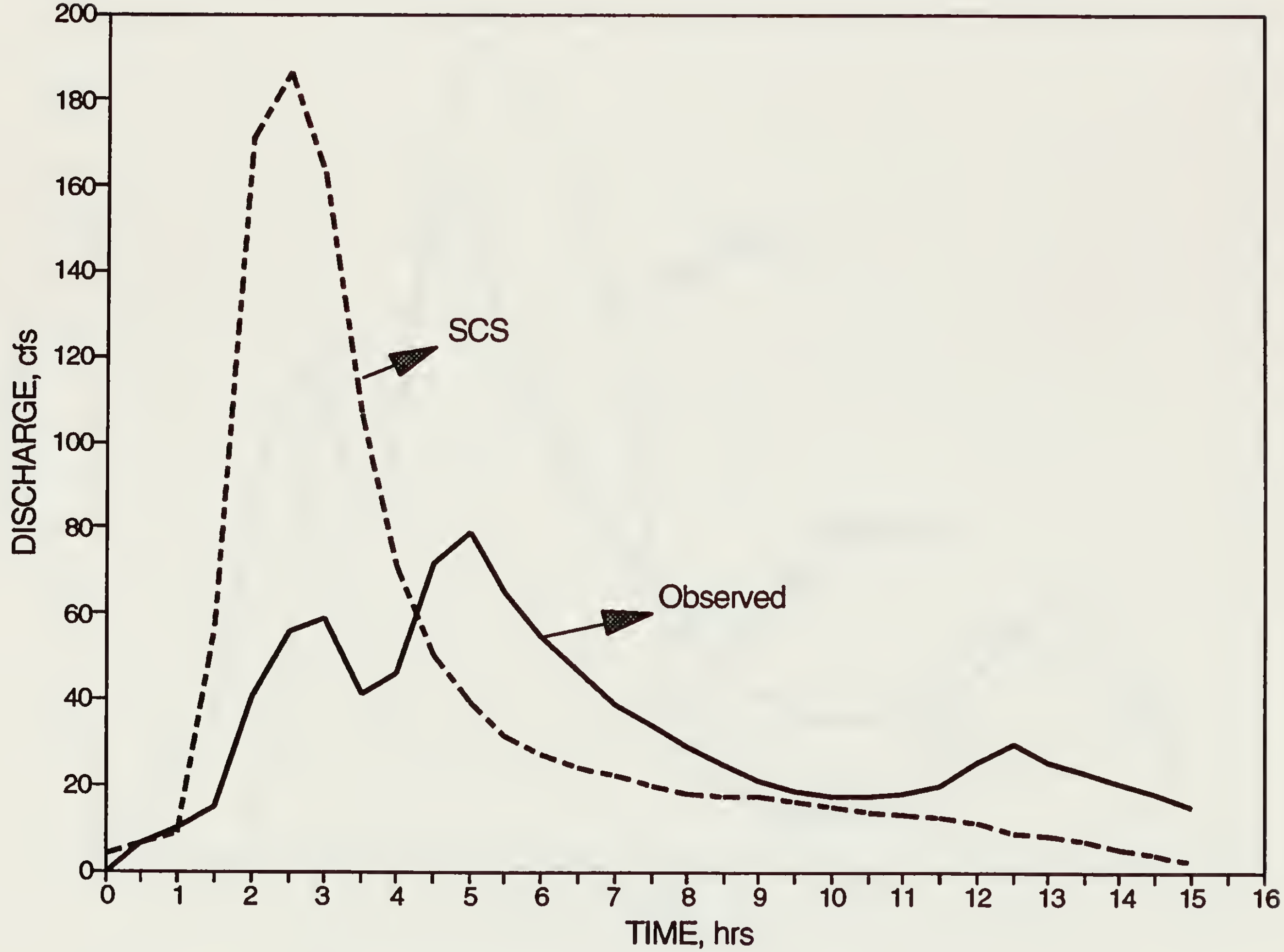

Fig. 11 Observed and SCS predicted stormflow hydrographs for Harrison Creek for event no. 4, April 16, 1987

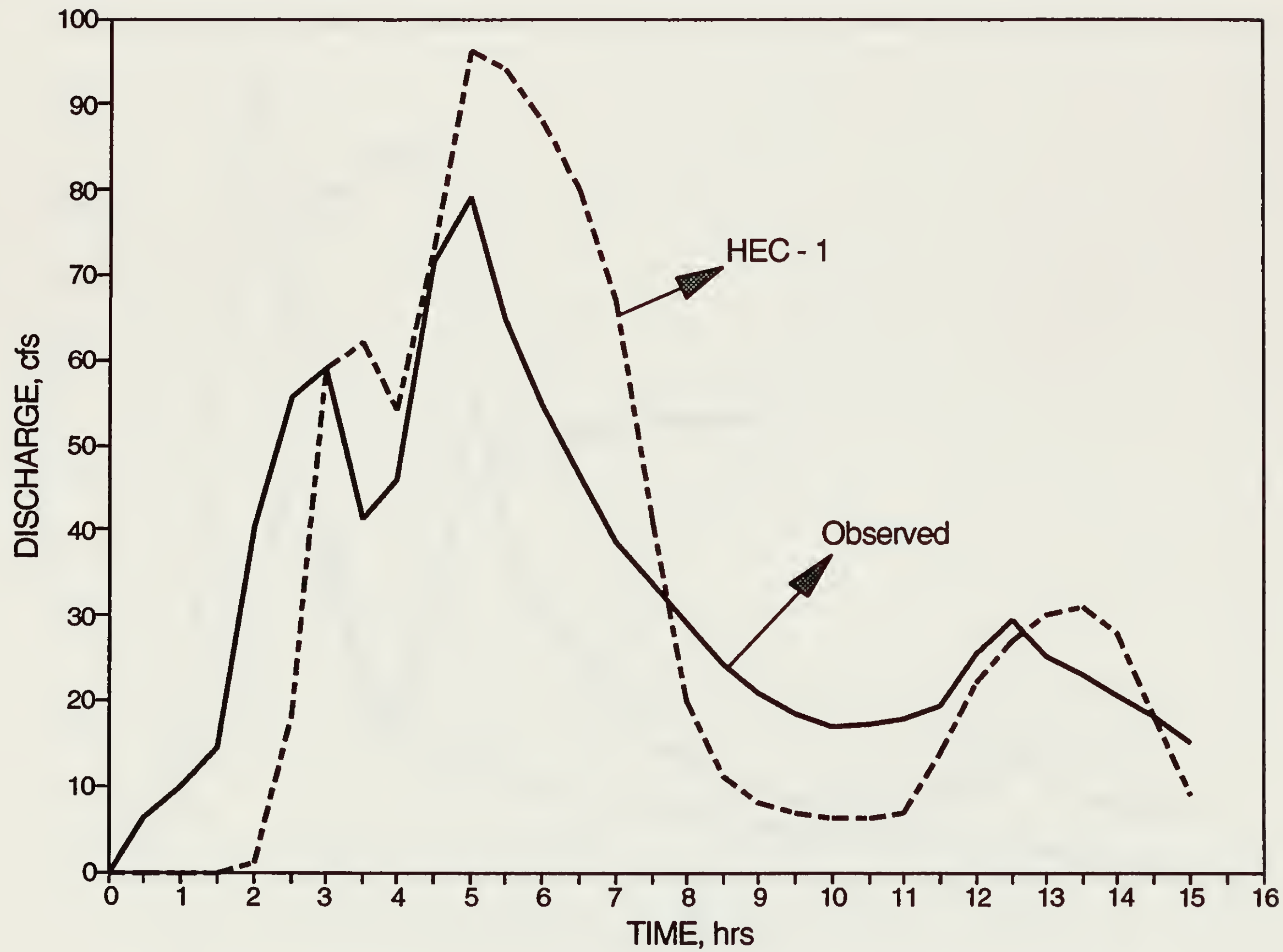

Fig. 12 Observed and HEC-1 predicted stormflow hydrographs for Harrison Creek for event no. 4, April 16, 1987

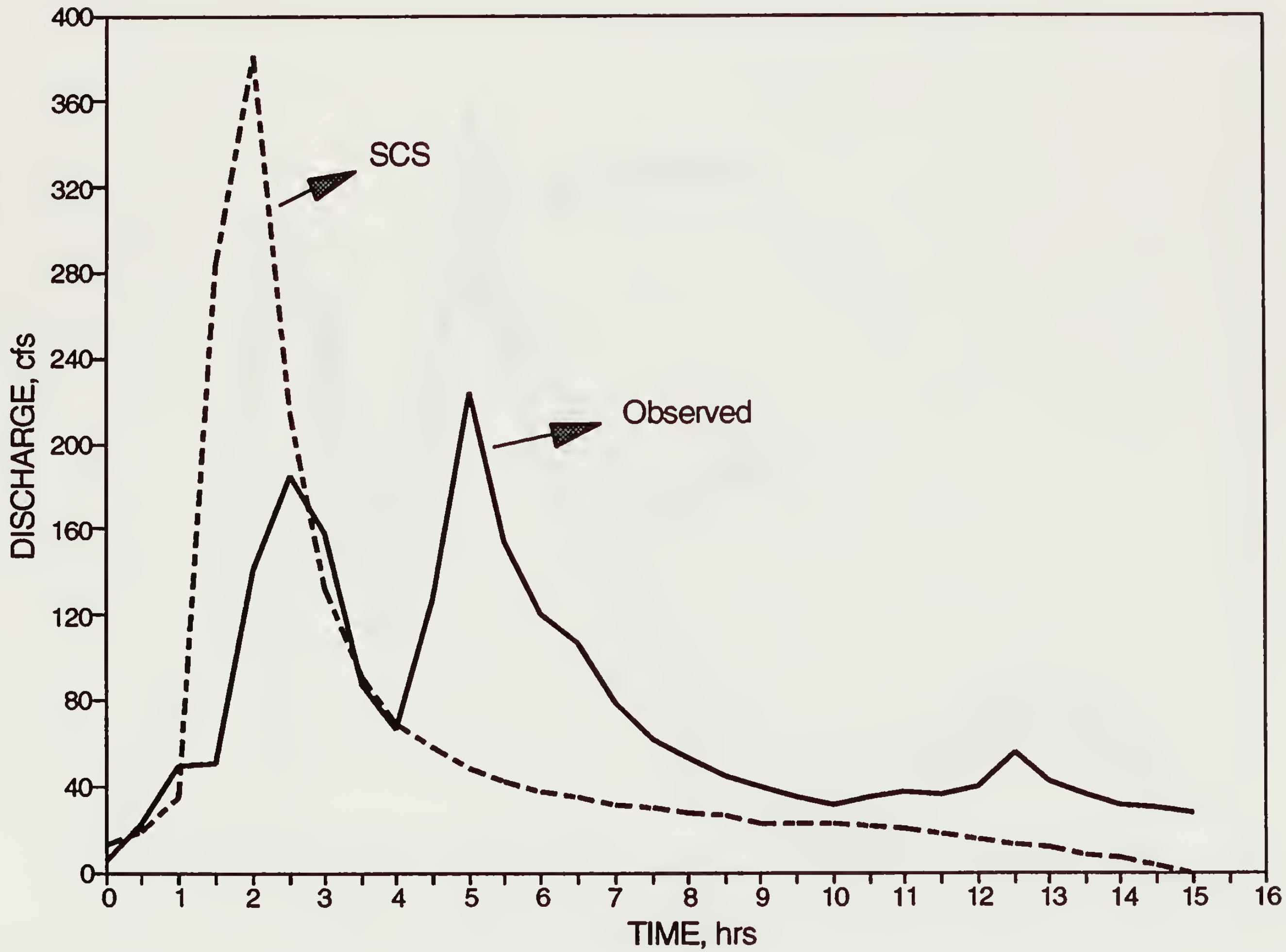

Fig. 13 Observed and SCS predicted stormflow hydrographs for Poore Creek for event no. 4, April 16, 1987

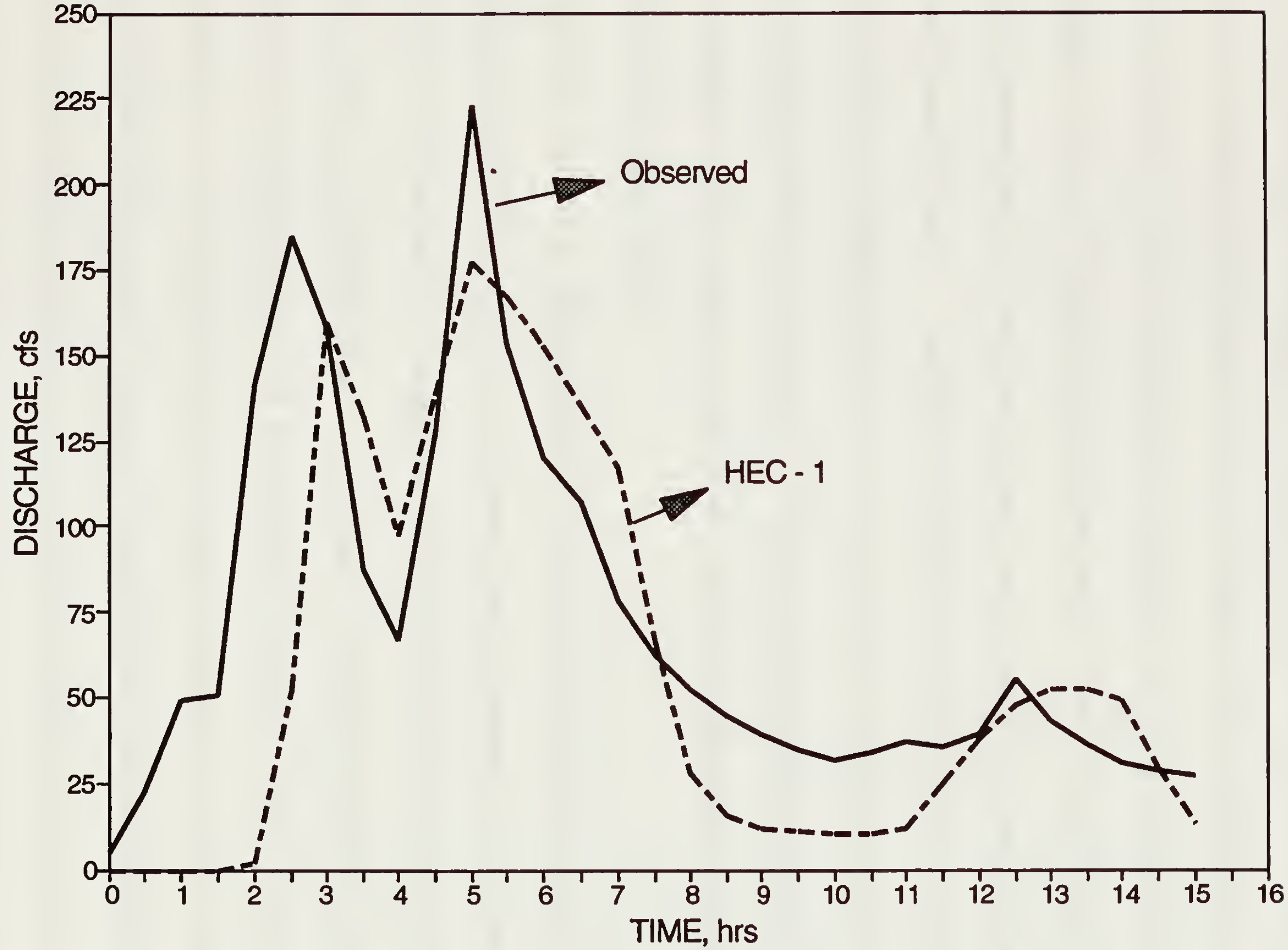

Fig. 14 Observed and HEC-1 predicted stormflow hydrographs for Poore Creek for event no. 4, April 16, 1987

conduct the calculations was developed in the early 1980's the tabular hydrograph-graphical peak discharge model has become extremely popular among civil engineers.

The inability of the tabular hydrograph method to accurately predict the shape and parameters of the stormflow hydrographs for Harrison and Poore Creeks is probably due to several factors in the structure of the model. The model begins with a rainfall amount uniformly imposed on the watershed over a specified time distribution, that time distribution being the long-term regional average of historical precipitation events. Thus, the predicted hydrograph may be a fair representation of the long-term regional average but a poor predictor for specific watersheds and specific events. The HEC-1 model is a more complex one that has a combination of different modeling options from simple to more complex and data intensive procedures, including parameter optimization, for design storm generation and routing runoff through the watershed. That greater sophistication in simulation procedures makes HEC-1 a better predictor of individual events.

One important factor that probably contributes to the stormflow prediction error of both the tabular hydrograph and HEC-1 models is that neither takes antecedent rainfall into account. Many hydrologic models use the 5-day antecedent rainfall as a way of estimating available soil storage at the onset of a precipitation event. An estimate of average available soil storage based on soils and land use distribution is used by the SCS and HEC-1 models. The impact of antecedent rainfall on the HEC-1 predictions of hydrograph parameters is shown in Tables 4 and 5. Extended rainfree periods prior to the onset of a rainfall event (5-day antecedent rainfall = 0) resulted in model predictions of peakflow and volume of stormflow that were higher than the observed. Where significant rainfall occurred the day prior to a modeled event (January 19,

Table 4. Stormflow characteristics predicted by the HEC-1 model for Poore Creek

Storm Event No.	Storm Event Date	Total 24-hrs Rainfall in	5-day Anteced. Rainfall in	Observed Stormflow Characterist.			Predicted Stormflow Characterist.		
				Peak Discharge cfs	Runoff Volume in	Time to Peak hrs	Peak Discharge cfs	Runoff Volume in	Time to Peak hrs
1	Aug 12, 86	2.50	0.71	86	0.35	7.0	192	0.92	11.0
2	Dec 24, 86	2.87	0.00	126	0.82	9.0	149	1.08	8.0
4	Apr 16, 87	3.01	0.89	223	1.65	5.0	177	1.35	5.0
5	Sep 05, 87	1.91	0.00	29	0.17	14.0	37	0.25	12.5
6	Feb 11, 88	1.81	0.00	50	0.41	9.0	83	0.43	10.5

Table 5. Stormflow characteristics predicted by the HEC-1 model for Harrison Creek

Storm Event No.	Storm Event Date	Total 24-hrs Rainfall in	5-day Anteced. Rainfall in	Observed Stormflow Characterist.			Predicted Stormflow Characterist.		
				Peak Discharge cfs	Runoff Volume in	Time to Peak hrs	Peak Discharge cfs	Runoff Volume in	Time to Peak hrs
2	Dec 24, 86	2.87	0.00	28	0.33	9.0	78	0.93	8.5
3	Jan 19, 87	2.04	1.15	49	0.79	7.0	32	0.49	9.0
4	Apr 16, 87	3.01	0.89	79	1.10	5.0	96	1.10	5.0
6	Feb 11, 88	1.81	0.00	16	0.25	7.0	40	0.30	7.5

1987 and April 16, 1987), the model predicted less stormflow volume and a lower peak discharge than the observed. For the storm of August 12, 1986, the 0.71 in of antecedent rainfall came four days prior to the modeled event and the model again over predicted stormflow. It is also interesting to note that the HEC-1 prediction of the stormflow peak and volume for the storm of April 16, 1987 was very close to the observed for Harrison Creek and significantly less than the observed for Poore Creek. That result is probably due to the greater proportion of undeveloped land in the Harrison Creek watershed. More infiltration and soil storage capacity per unit area were available there when the rain started than in the Poore Creek watershed.

These data illustrate an important principle in the application of hydrologic models, particularly the rather simple, easy-to-use types such as the SCS package. Rainfall-stormflow models are designed to predict the average hydrograph that might be produced by a particular size and duration of rainfall event. That HEC-1, as illustrated here, does not accurately predict the hydrograph of every event does not in any way diminish its utility in studies of small urbanizing watersheds. The model does a good job of predicting average hydrographs across a wide range of watershed conditions and rainfall amounts.

To compare the common methods of predicting the peak discharge of design storms, the peak discharge of the 10, 25, 50 and 100-year return period, 24-hour storms were calculated with the SCS methods, HEC-1 and the rational formula (Table 6 and Appendix Table 13). Even though the two SCS prediction models were less accurate than HEC-1 at predicting the peak discharge of individual historical events (Table 2), those three methods and the rational formula were not far apart in predictions of peak discharge for the "average" events represented by

Table 6. Peak discharges of design storms predicted by four different methods

Watershed name	Frequency of return period	Total 24-hr rainfall	Peak Discharge by			
			SCS tabular hydrograph	SCS graphical pk disch.	HEC-1 SCS loss function	Rational Formula
	yrs	in	cfs	cfs	cfs	cfs
POORE CREEK	10	5.7	1196	936	1111	1256
	25	6.3	1373	1075	1359	1468
	50	7.0	1611	1263	1572	1680
	100	7.9	1851	1453	1792	1800
HARRISON CREEK	10	5.7	600	495	576	596
	25	6.3	700	578	716	695
	50	7	835	675	843	800
	100	7.9	968	801	973	863

design storms. Design storms are "average" in terms of antecedent conditions and the distribution of cumulative rainfall over the duration of the event. The predictions of peak discharge by the graphical peak discharge method were in the range of 15-25 percent lower than those calculated by the other methods. That is probably due to the fact that the simplistic approach of the graphical peak discharge method assumes a homogeneous watershed. However, because of that very simplicity and ease of application, the graphical peak discharge method is widely used for preliminary design of stormwater detention structures.

To predict the parameters and shape of the stormflow hydrographs for the four design storms, the HEC-1 method was used (Table 7 and Figures 14 and 15). Expressing peak discharge and stormflow volume on an area basis shows that the model consistently predicted higher runoff for Poore Creek. However, the predicted differences in stormflow are much smaller than for the historical events (Table 1) because the differences in infiltration capacity and soil storage have less impact on stormflow for the larger storms. Note the classic shape of the "average" hydrographs in which the standard rainfall distribution is assumed. The more flashy nature of the Poore Creek watershed compared to the Harrison Creek watershed is evident in these predicted hydrographs. Poore Creek has greater volumes of stormflow and higher peak flows than does Harrison Creek but the hydrographs extend over essentially the same time period and the rates of hydrograph rise and recession are greater for Poore Creek than for Harrison Creek.

All of the modeling analyses of the characteristics of stormflow in Poore and Harrison Creeks support what was shown by comparisons of stormflow for historical events, that the Poore Creek discharge is more responsive to rainfall than that of Harrison Creek. As for the

Table 7. Stormflow parameters of design storms predicted by the HEC-1 model

Return Period years	24-hour Rainfall in	Peak Discharge Poore cfs	Peak Discharge Harrison cfs	Peak Discharge Poore cfsm	Peak Discharge Harrison cfsm	Stormflow Volume Poore in	Stormflow Volume Harrison in
10	5.7	1111	576	1081	846	3.3	3.0
25	6.3	1359	716	1322	1051	4.0	3.7
50	7.0	1572	843	1529	1237	4.7	4.3
100	7.9	1792	973	1743	1428	5.4	5.0

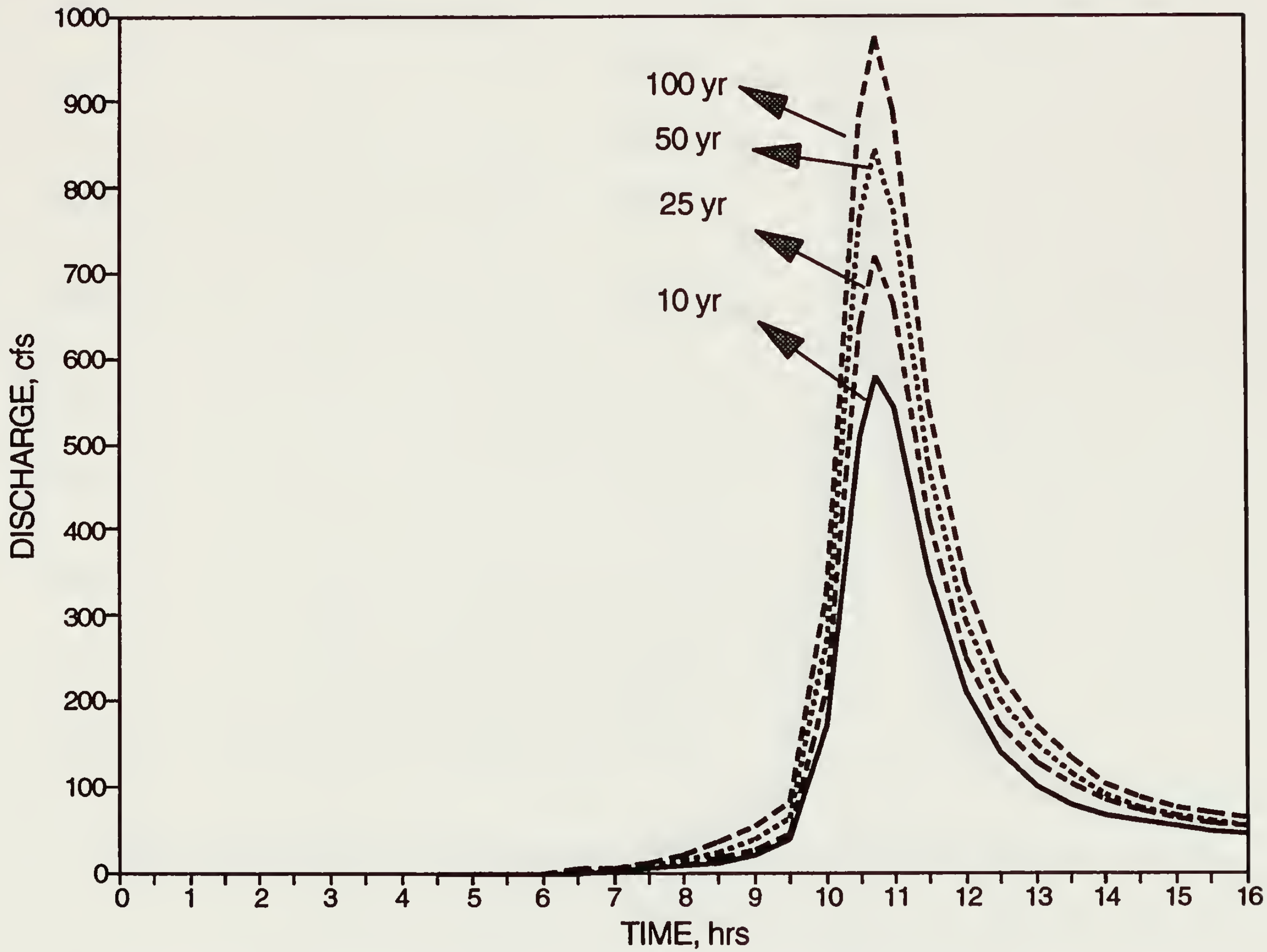

Fig. 14 HEC-1 predicted stormflow hydrographs for rainfall of different return periods, Harrison Creek , impervious area = 13.5 %

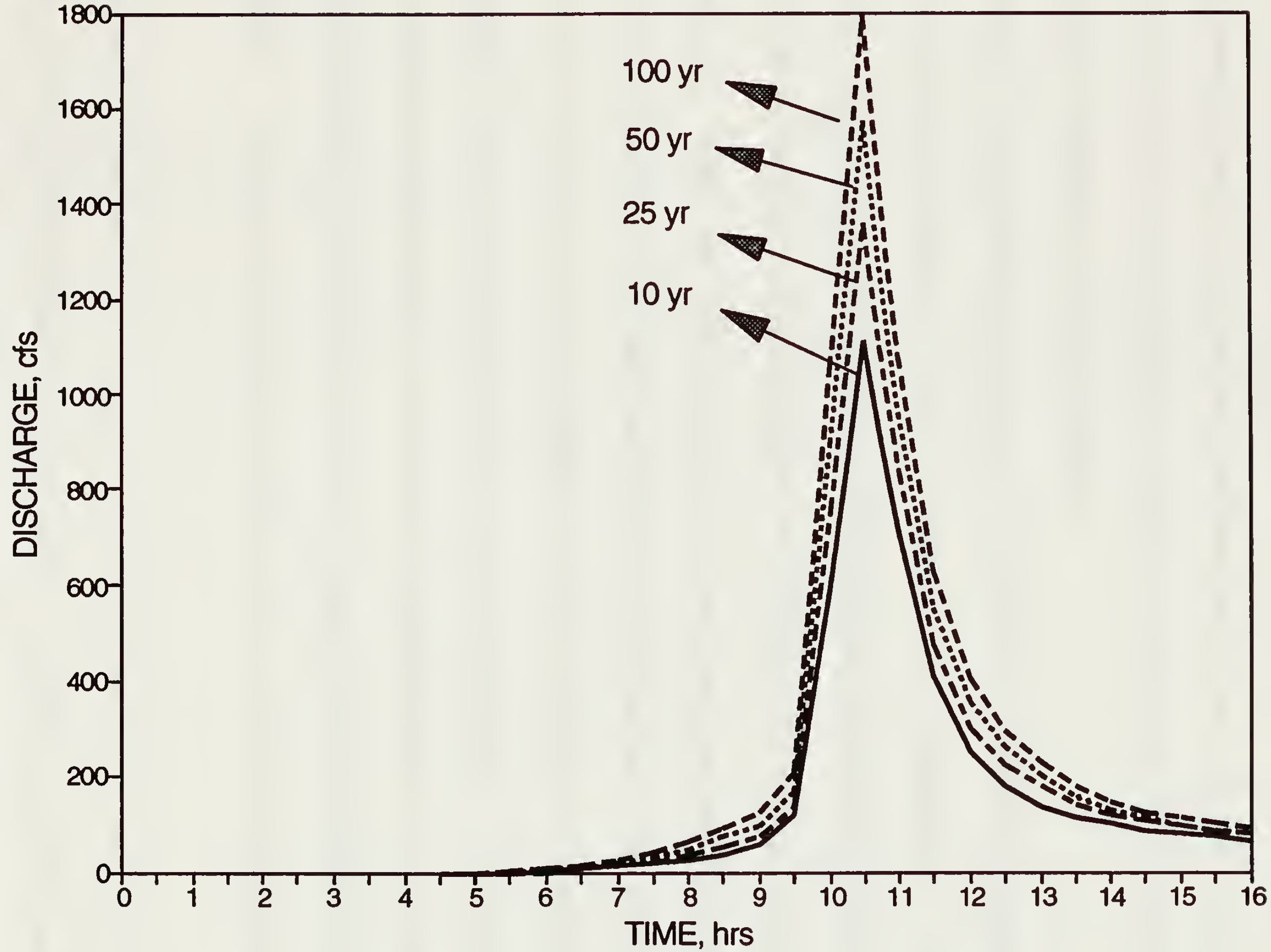

Fig. 15 HEC-1 predicted stormflow hydrographs for rainfall of different return periods, Poore Creek, impervious area = 28.0 %

historical events, the question still remained at this point in the analysis about the reasons for those differences. The soils and topography of the watersheds are similar, but the differences in stormflow character when peak flow and volume are expressed on an area basis were much too great to be explained by differences in shapes of the subwatersheds and routing of stormflow through the channel systems. Thus, the last simulation analysis was designed to test the central hypothesis of this study, that the hydrologic differences between Poore and Harrison Creeks were due to land use differences in the watersheds.

The last step in the hydrologic analysis was to use HEC-1 to predict the characteristics of stormflow from Poore and Harrison Creeks at different levels of development. (Table 8 and Figures 16-18). For the 10-year 24-hour storm, the discharge peak (cfsm) and total stormflow volume for Poore Creek under existing conditions were 28% and 12% greater than for Harrison Creek respectively. At the time of the study the Poore Creek watershed had 28.0% impervious surface and the Harrison Creek watershed had 13.5% impervious surface. With impervious area at 13.5% for both watersheds, the model predicts that there would be little difference in peak flow or stormflow volume on an area basis for the 10-year 24-hour storm. The hydrographs of Figure 16 dramatically illustrate that the observed hydrologic differences between the stormflows from Poore and Harrison Creeks are due mainly to the higher level of development in the Poore Creek watershed. For the same land use conditions, the stormflow hydrographs are very similar.

The predicted stormflows for the 10-year 24-hour storm that would result from increased development are shown in Table 8 and Figures 17 and 18. Increasing impervious area from its existing 28.0% to 42.5% in the Poore Creek watershed would increase peak discharge (cfsm)

Table 8. Stormflow parameters for the 10-yr 24-hr storm for different development scenarios predicted by the HEC-1 and SCS Graphical Peak Discharge Methods

Percent	HEC-1 Peak Discharge				Stormflow Volume		SCS Graphical Peak Discharge			
Impervious Area	Poore cfs	Harrison cfs	Poore cfsm	Harrison cfsm	Poore in	Harrison in	Poore cfs	Harrison cfs	Poore cfsm	Harrison cfsm
13.5	945	576	919	846	3.05	3.03	765	495	744	727
28	1111	676	1080	992	3.4	3.38	936	646	910	948
42.5	1290		1255		3.8		1143	786	1112	1154

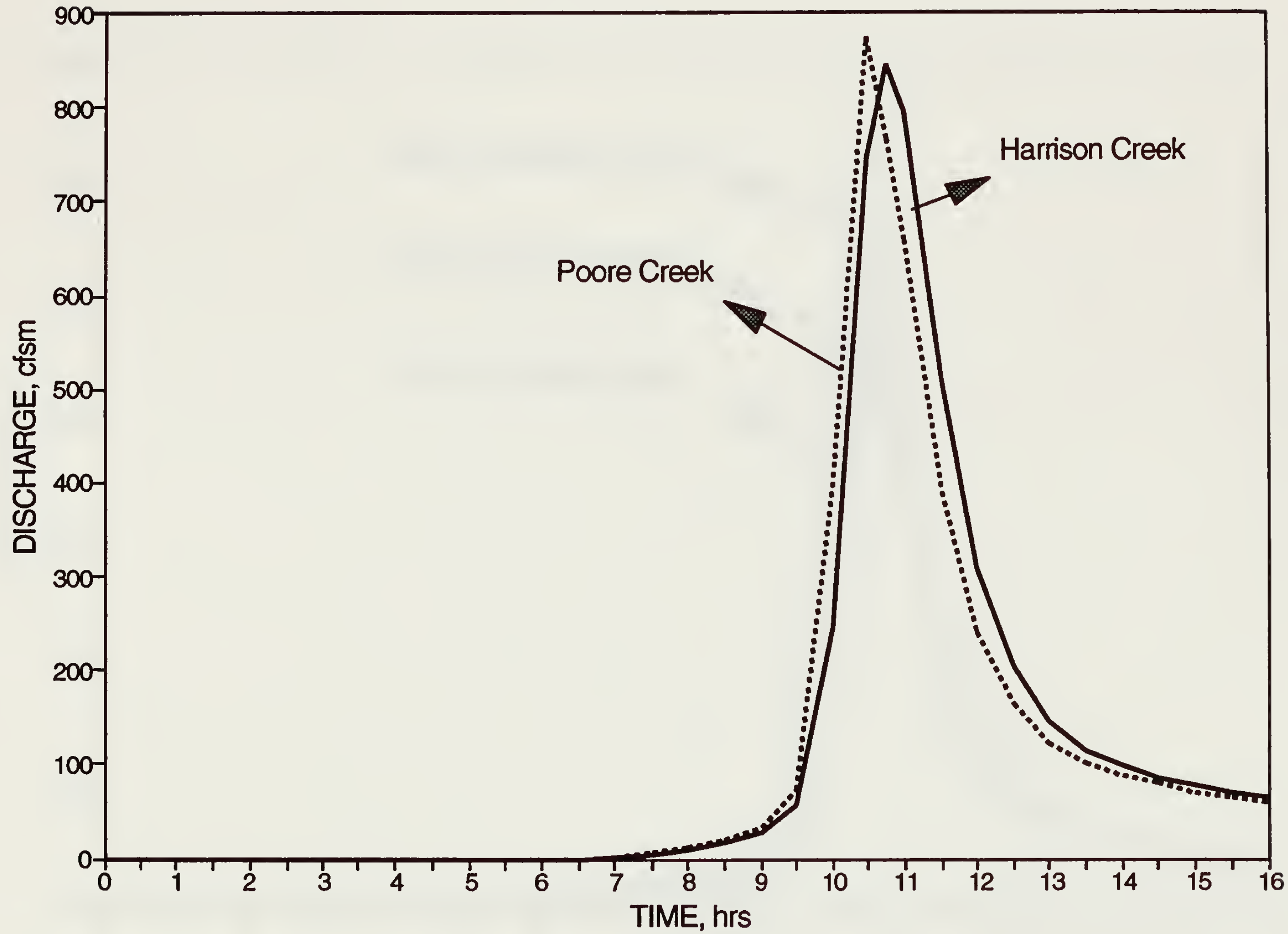

Fig., 16 HEC-1 predicted stormflow hydrographs for 10-yr 24-hr design storm for Poore and Harrison Creeks for 13.5 % impervious area

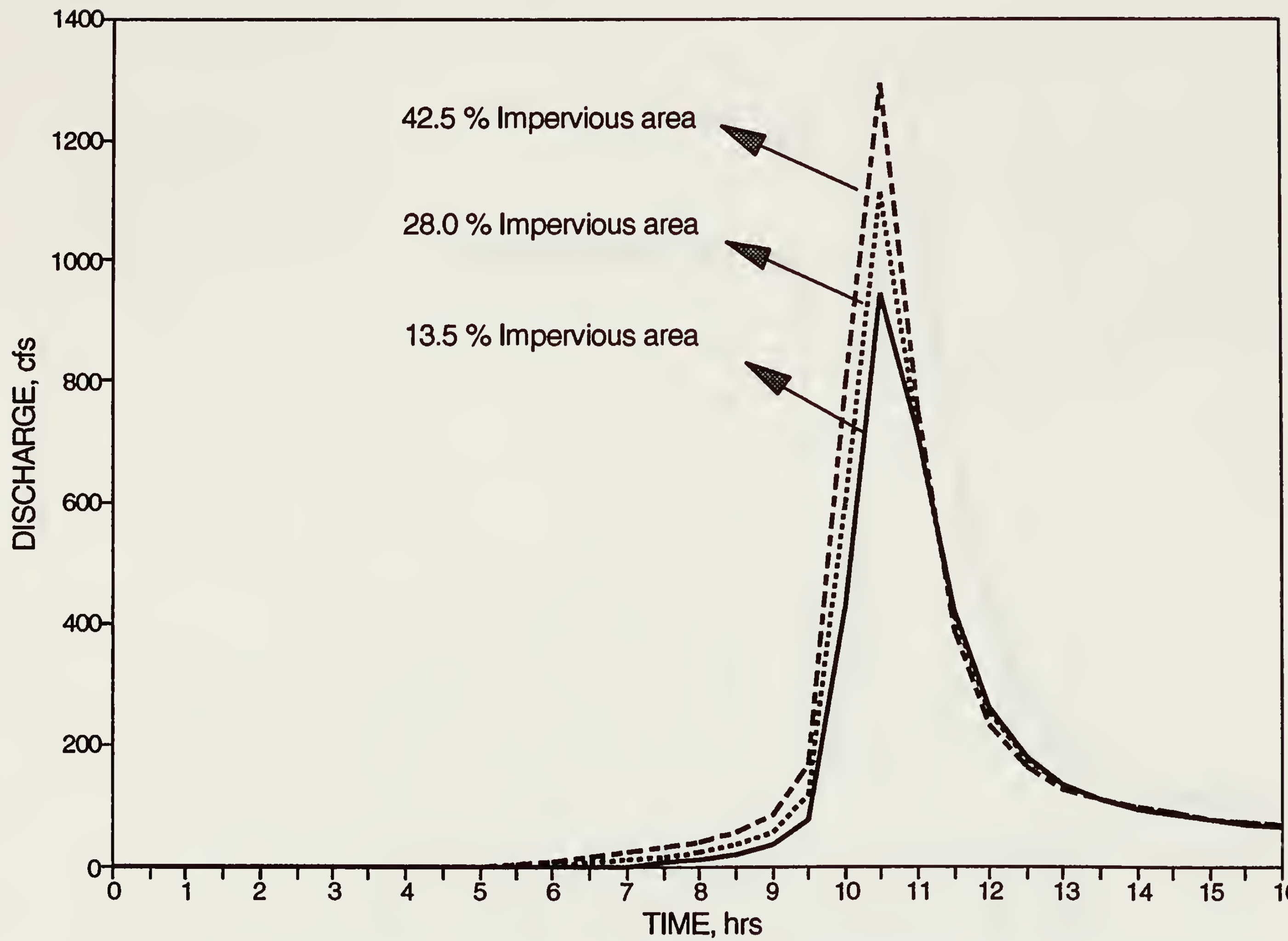

Fig. 17 HEC-1 predicted stormflow hydrographs for 10-yr 24-hr design storm for Poore Creek

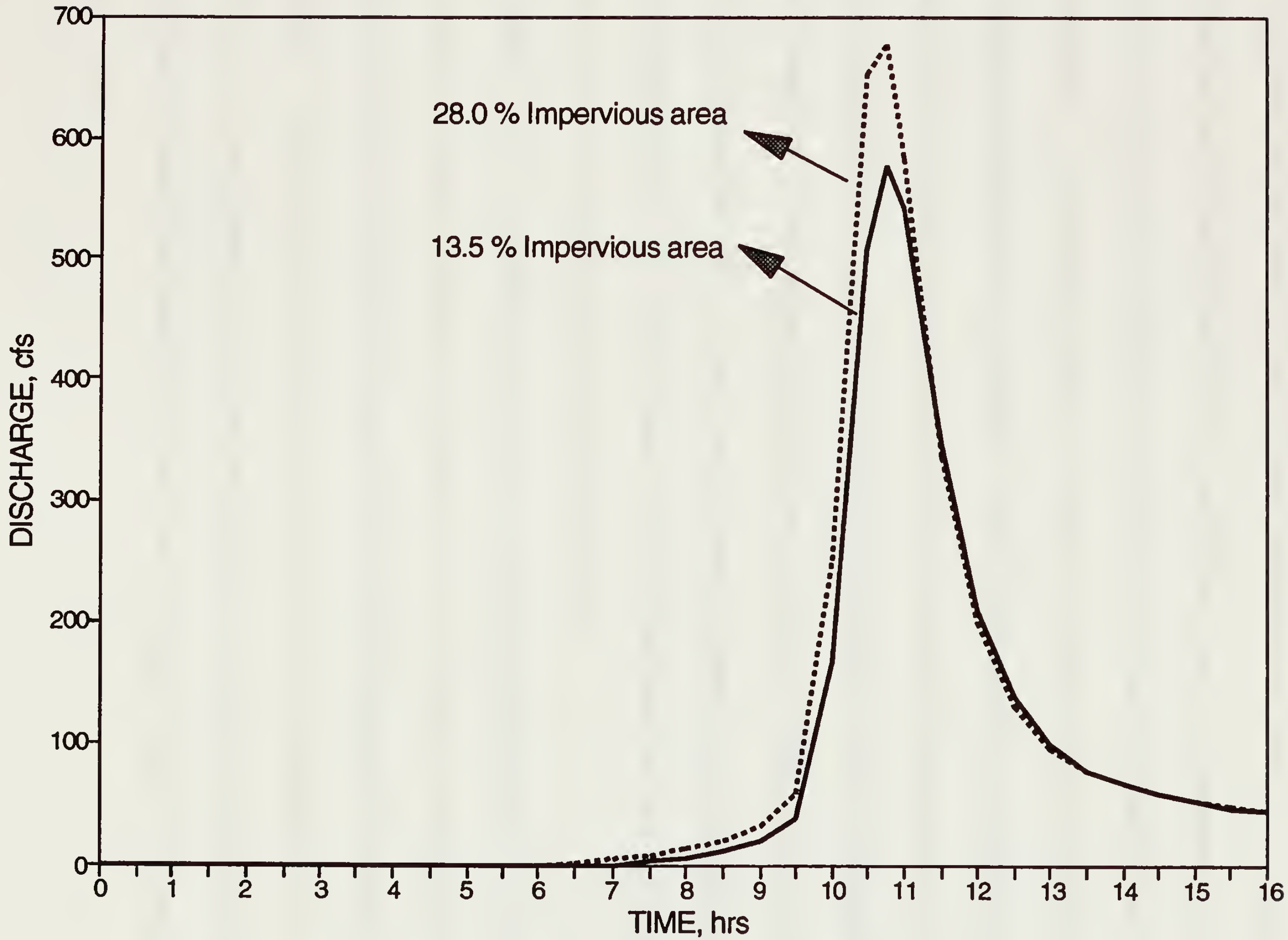

Fig. 18 HEC-1 predicted stormflow hydrographs for 10-yr 24-hr design storm for Harrison Creek

by 16% and stormflow volume by 12%. The model predicts that increasing impervious surface in the Harrison Creek watershed to the 28.0% level present in the Poore Creek watershed would increase peak discharge (cfsm) by 17% and stormflow volume by 12%.

The actual impact on the stream channel is the key issue to be addressed here. For Harrison Creek the predicted peak of stormflow for the 10-year 24-hour storm will increase from 575 cfs to 676 cfs with an approximate doubling of the existing low level of development, a 17% increase in peak flow. On the average, each 1% increase in impervious area, therefore, results in a 1.2% increase in the peak rate of stormflow. With a predicted increase in peak stormflow of 16% resulting from increasing impervious surface from 28.0% to 42.5%, that rate of increase of peak flow is predicted to be about 1.1% for each 1% increase in impervious area for the Poore Creek watershed. Thus, expanding development results in a continual increase in the amount of impervious surface which, in turn, causes a steady increase in peak flows and results in long term destabilization of a stream channel. The channel must respond to the steadily increasing stormflow by becoming larger to carry those flows.

The simplest way to ameliorate the impact of increasing development on increasing stormflow is to provide detention storage in the channel system. Detention storage is short-term storage that has the effect of changing the shape of the stormflow hydrograph downstream from the storage basin. Holding water and releasing it more slowly into the channel than would be the case without the basin increases the stormflow hydrograph duration and reduces the peak flow. The volume of water represented by the stormflow hydrograph simply moves through the channel more slowly.

The detention pond option of the SCS package of models was used for the preliminary calculation of detention basin storage that would provide discharge control for the Poore Creek and Harrison Creek watersheds. The peak flow predicted by the graphical peak discharge method was used for these calculations since the detention pond option is coupled with it in the SCS software (Table 8). Using the 10-year, 24-hour design storm, a detention basin with a storage capacity of 49.4 acre-feet (1 acre-foot is 1 acre of water 1 foot deep or 43,560 ft^3) would be required in Poore Creek to reduce peak flow from 1143 cfs to 765 cfs. A basin of that size would have the capacity to control the predicted peak flow from the Poore Creek watershed at 42.5% impervious area to that predicted for 13.5% impervious area. Controlling the peak flow under existing conditions (28.0% impervious area) to that predicted for 13.5% impervious area would require 34.5 acre feet of storage, reducing peak flow from 936 cfs to 765 cfs. Similar calculations for Harrison Creek showed that storage capacity of 34.6 acre-feet would be needed to control the predicted peak flow of 786 cfs at 42.5% impervious area to the predicted peak flow of 495 cfs for existing conditions (13.5% impervious area). The predicted peak flow of 646 cfs at 28% impervious area could be controlled to that predicted for existing conditions with 25.3 acre-feet of detention storage.

Water Quality

The water quality analyses that were conducted for this study were intended to provide a general overview of the quality of the water, particularly with regard to factors that may be important in human contact with that water. An exhaustive study of water constituents, temporal and spatial variation, and potential pollutant sources was not within the scope of our objectives. An important issue for the battlefield management is visitor use of the streams, how that use

may affect the streams, and how water quality may affect the visitors. Artifact hunters are frequent users of the stream channels of Petersburg National Battlefield. Since the use of metal detectors and the disturbance of soil is prohibited, ardent hunters of artifacts have discovered that the stream channels are a rich source of artifacts where the erosive power of high streamflows is conducting the work of excavation from the soil. Also the fascination that man has for water features simply draws many visitors to hike along the channels (there is a well-worn trail along each channel) or to kick off their shoes and go wading. Therefore, water quality is an issue, not only as an indicator of environmental degradation, but also for visitor health and safety. The analyses for dissolved and suspended constituents represent physico-chemical properties of the water and large number of samples must be analyzed to detect trends. Sampling of macroinvertebrate populations provides insight into the impact that water quality has on aquatic organisms - an integrator over time of cumulative effects.

Dissolved and Suspended Constituents

The water quality analyses represents a relatively limited cross-section of the water quality variation. Sampling on a regular weekly schedule meant that few stormflow samples were taken. However, the data does show general trends of water quality for stream baseflows and the conditions of the streams when visitors are most likely to be walking in them. The data for each parameter are shown in a consistently organized sequence of charts (Figures 19-33) in which all data within individual months are pooled among years to show monthly means. Examination of the data showed that there was limited variation in water quality among years. However, seasonal variation within years and some differences between streams and between the upstream and downstream sampling points on a particular stream were apparent. The State of Virginia

has no water quality criteria applicable to small streams like Poore and Harrison Creeks so all the criteria referred to were taken from Flora et al., 1984, which is a compilation of recommended criteria from several sources.

Values of turbidity were low, somewhat variable among seasons and between stream sampling points, but there was no difference between streams (Figures 19-21). Turbidity, of course, is highly correlated with discharge and the higher values most likely were due to samples in the monthly data set being taken during periods of higher flows. Variation between locations on a stream is also common because turbidity is influenced by water velocity and turbulence. Turbidity is a measure of the reduction in light transmission through a water sample that is caused by suspended material. The values shown for Poore and Harrison Creek (in nephelometric turbidity units, ntu) represent the normal range for baseflows in such small creeks. Values of several thousand or greater if maintained for relatively long periods can be detrimental to aquatic organisms, either because of reduced light penetration or the direct effects of suspended matter on fish and other aquatic animals.

Total suspended solids (TSS) is, like turbidity, a measure of the material in suspension and the pattern of variation is similar to that for turbidity (Figures 22-24). The predominantly baseflow values were relatively low.

Total dissolved solids (TDS), as the term implies, is a measure of all the dissolved constituents in the water column. The TDS values for Poore and Harrison Creeks invoke some interesting questions about the factors that account for the variation within and between streams. (Figures 25-27). In Harrison Creek, the concentration of dissolved solids was consistently higher at the upstream station than at the downstream station. That reduction may be due to

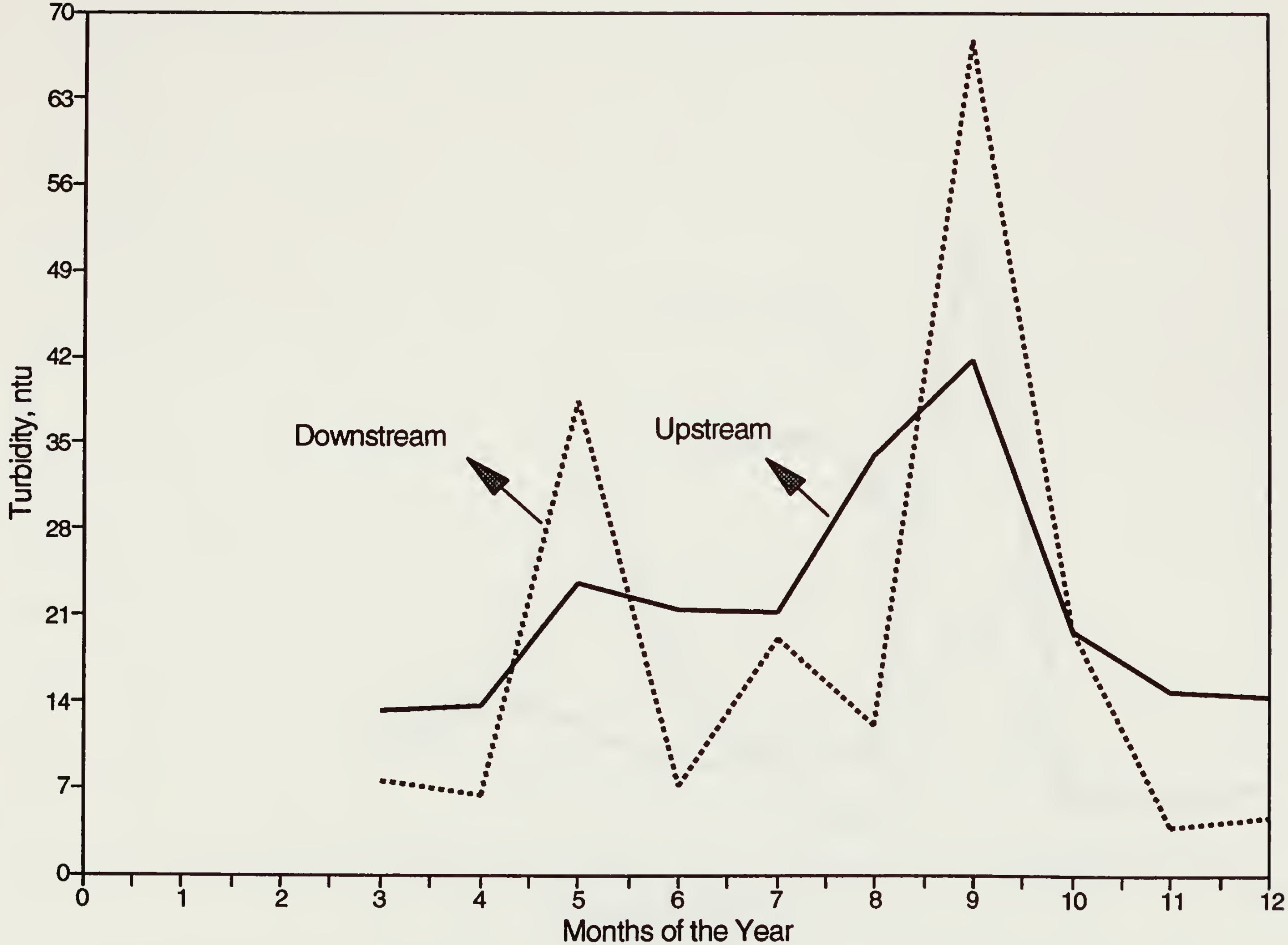

Fig. 19 Mean monthly (1986 - '88) turbidity for the Harrison Creek sampling stations

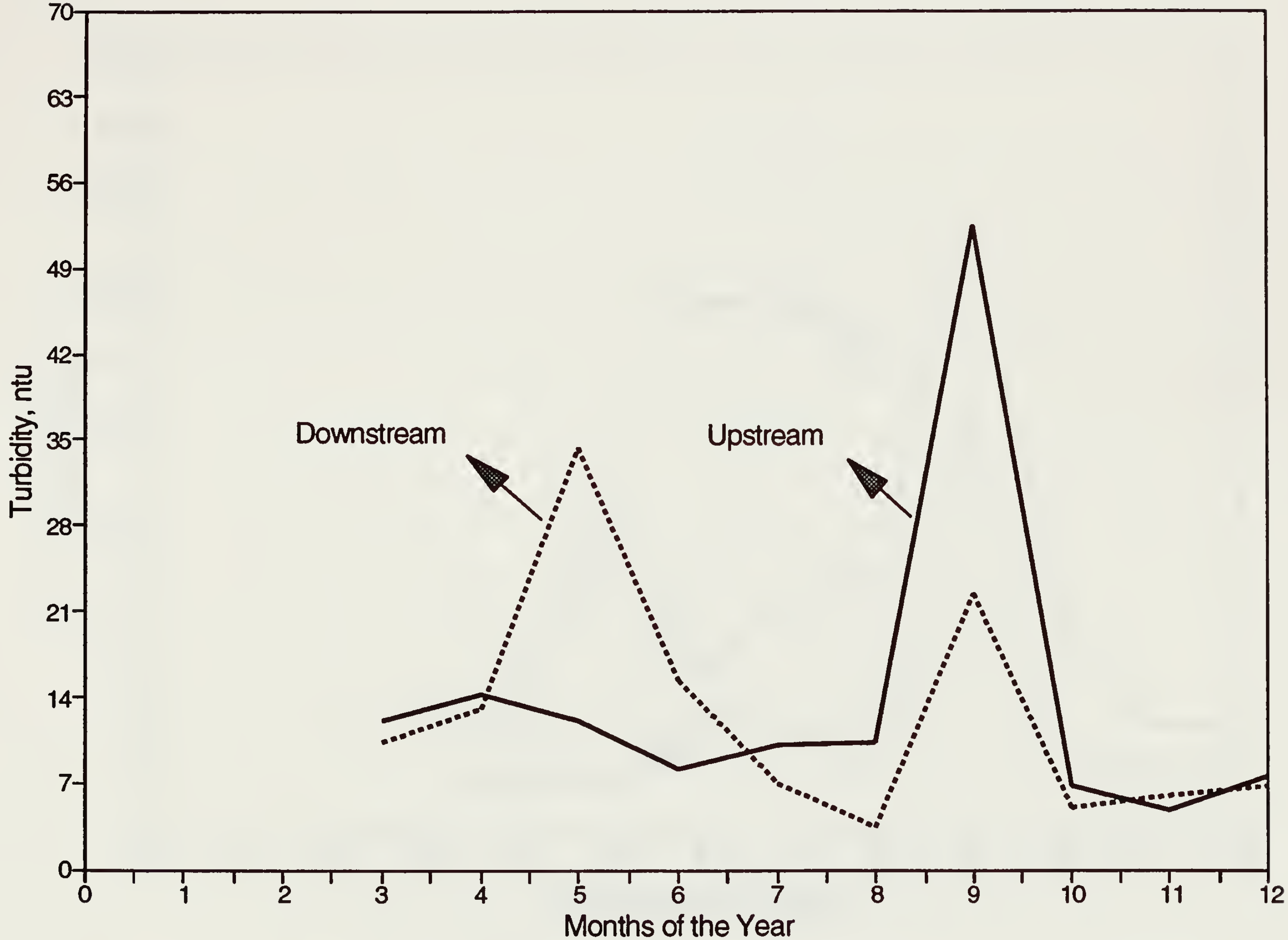

Fig. 20 Mean monthly (1986 - '88) turbidity for the Poore Creek sampling stations

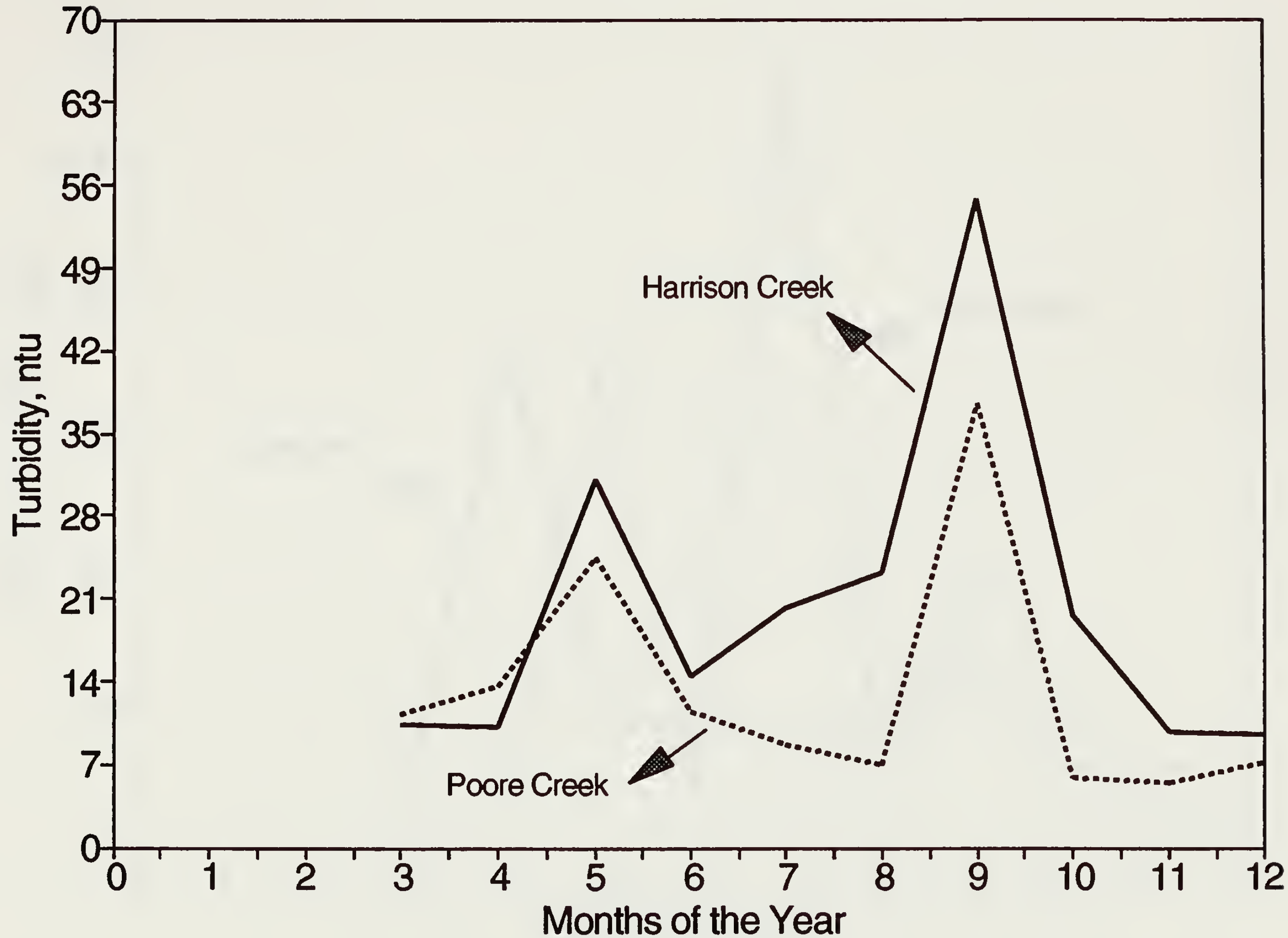

Fig. 21 Mean monthly (1986 - '88) turbidity, mean of the upstream and downstream stations

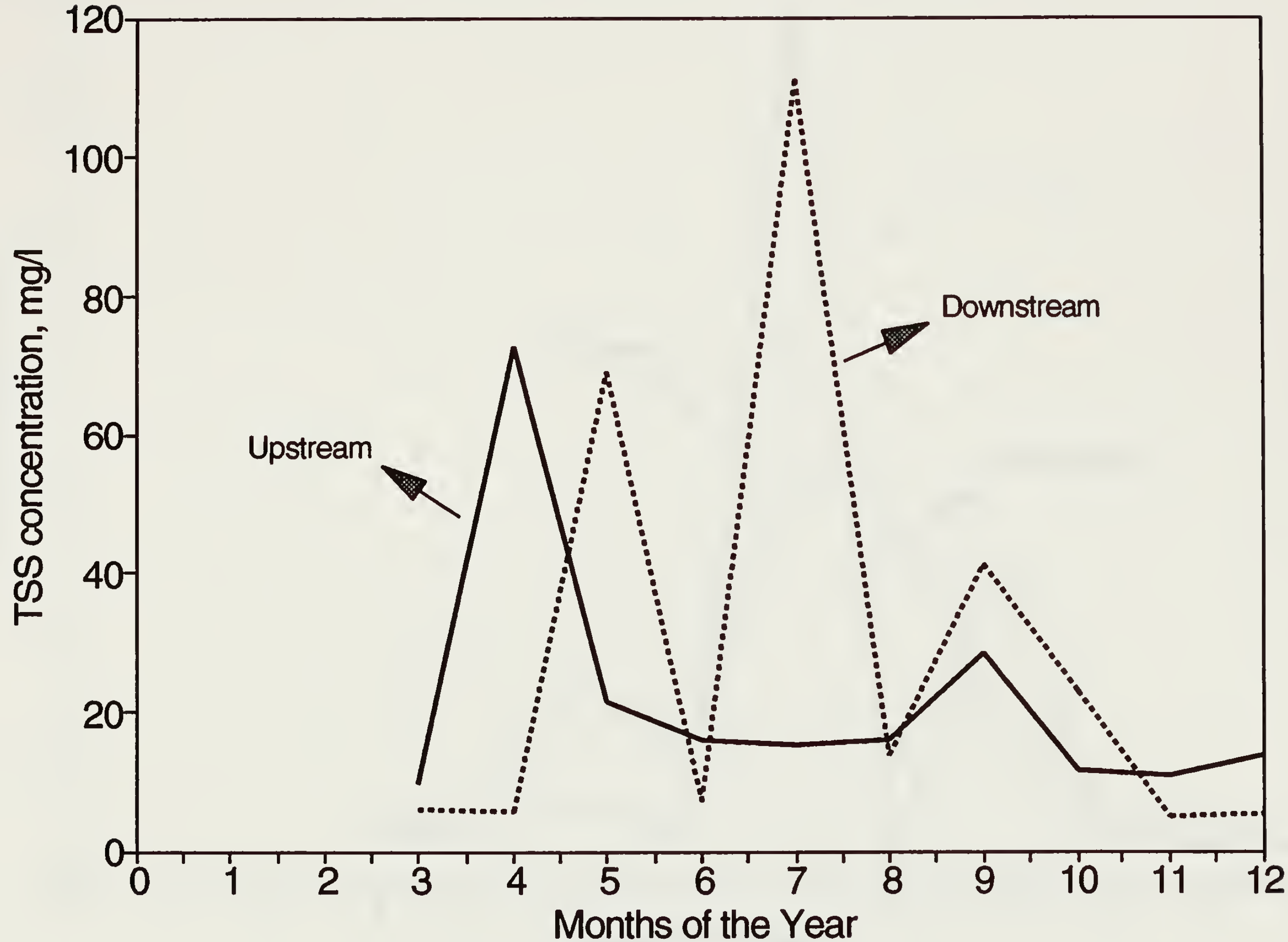

Fig. 22 Mean monthly (1986 - '88) TSS concentration for the Harrison Creek sampling stations

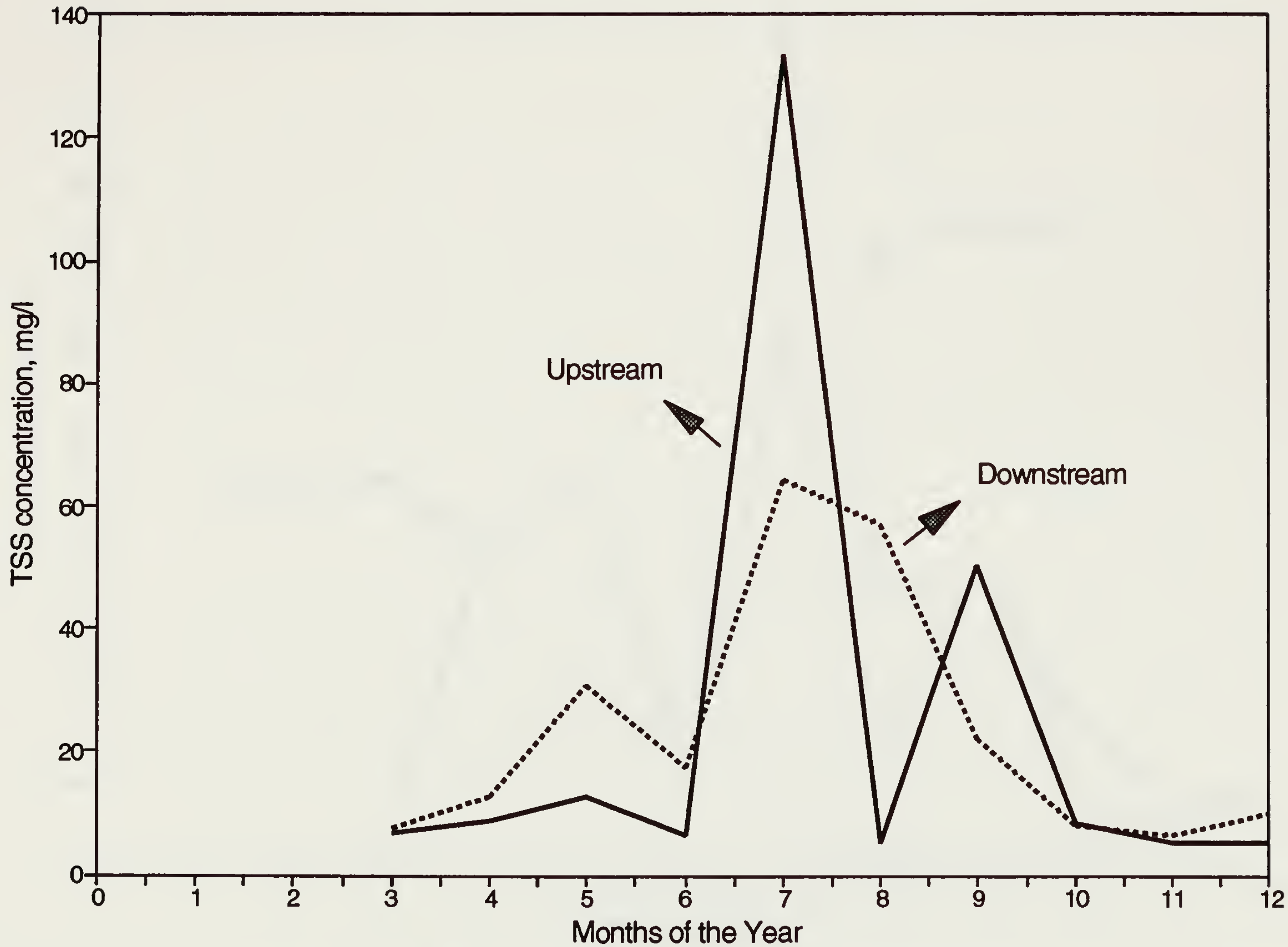

Fig. 23 Mean monthly (1986 - '88) TSS concentration for the Poore Creek sampling stations

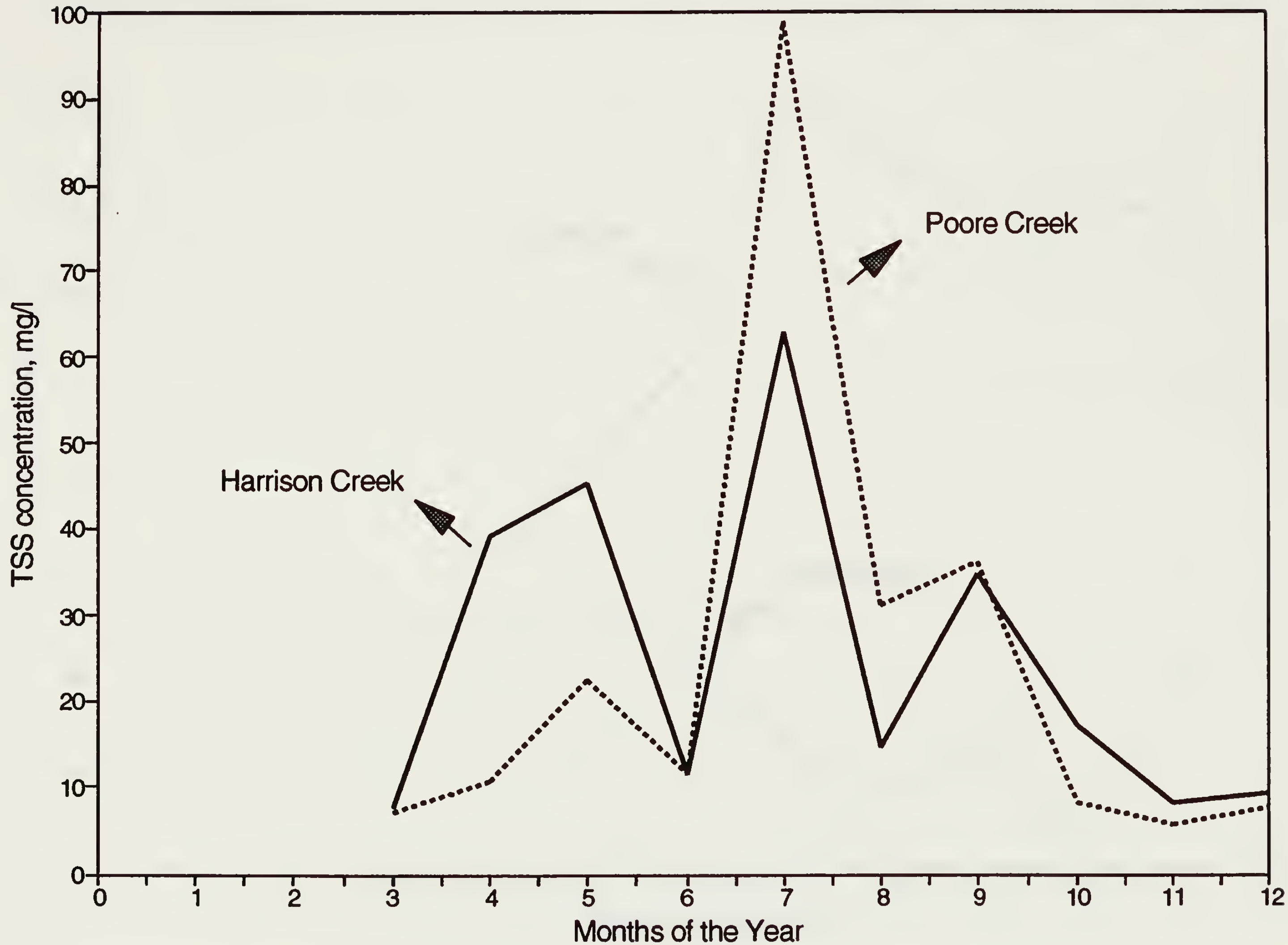

Fig. 24 Mean monthly (1986 - '88) TSS concentration, mean of the upstream and downstream stations

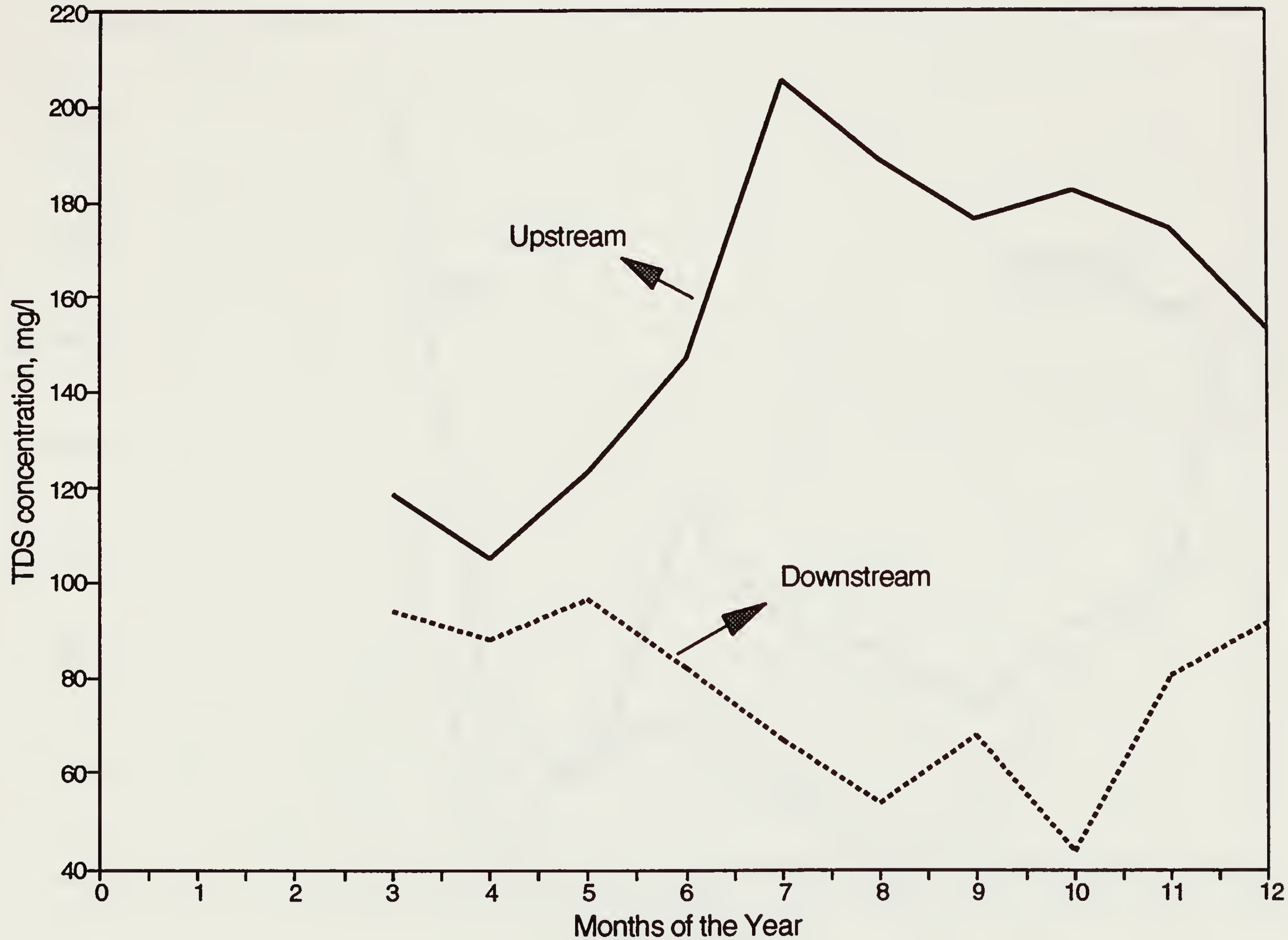

Fig. 25 Mean monthly (1986 - '88) TDS concentration for the Harrison Creek sampling stations

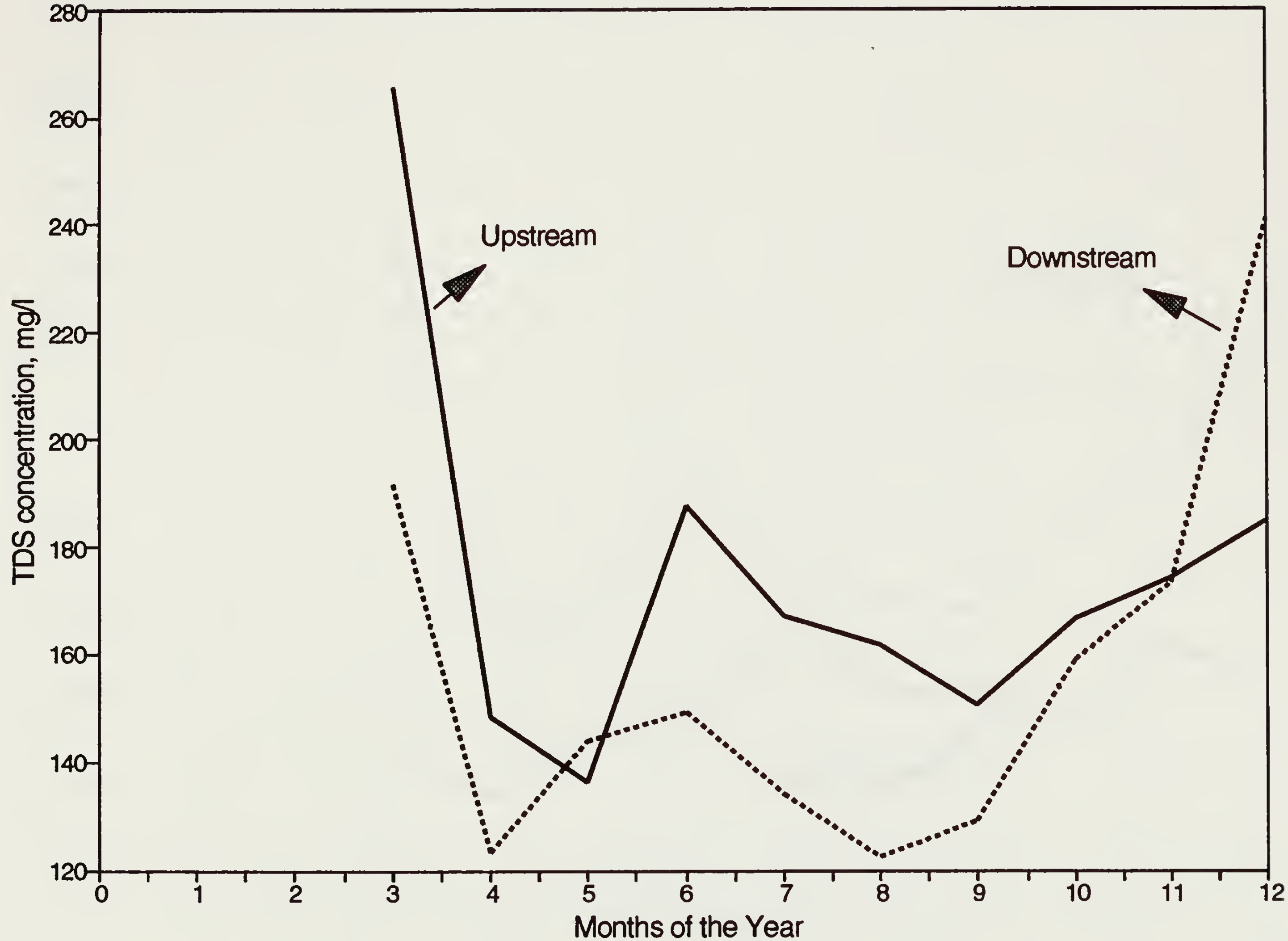

Fig. 26 Mean monthly (1986 - '88) TDS concentration for the Poore Creek sampling stations

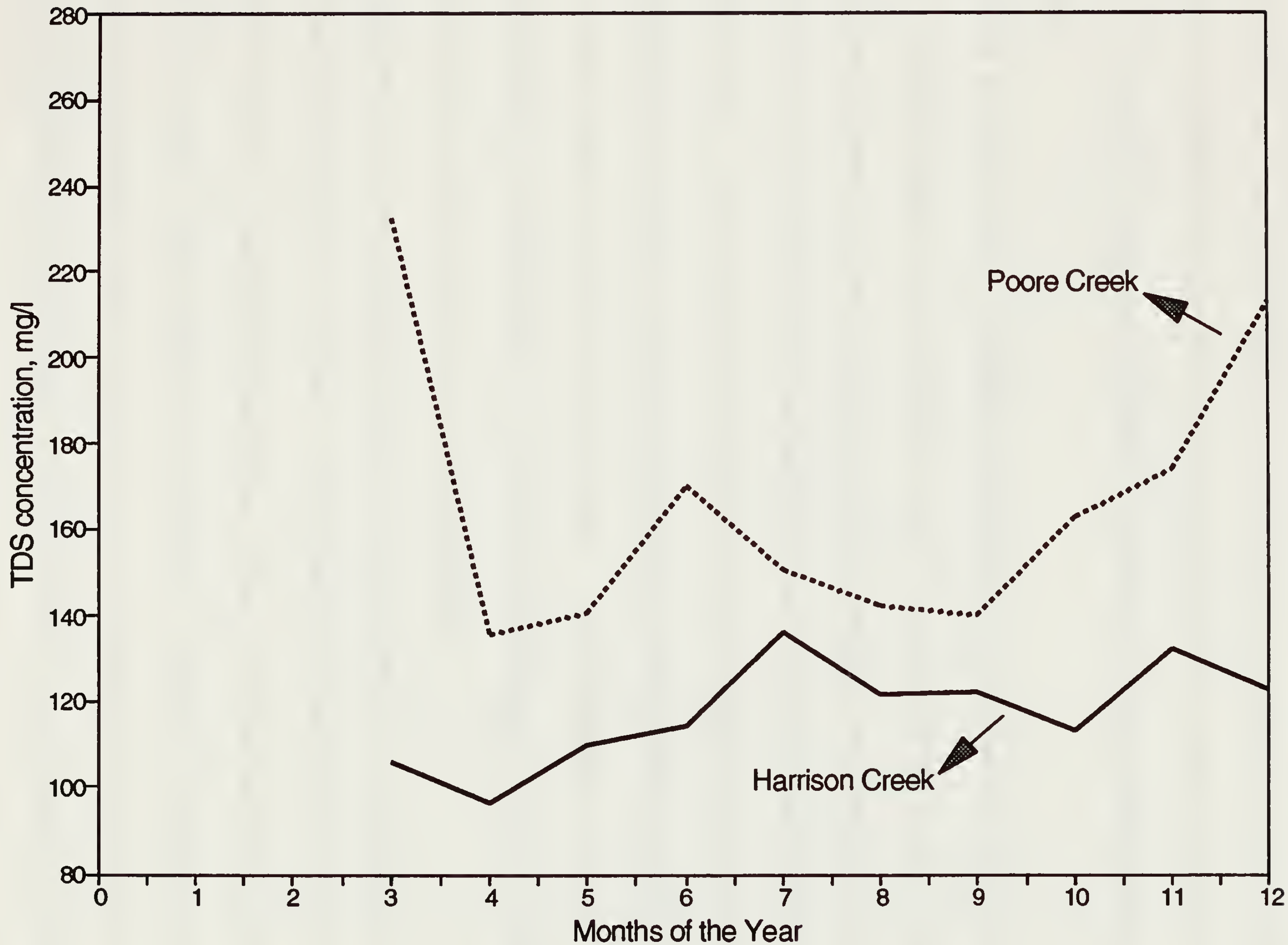

Fig. 27 Mean monthly (1986 - '88) TDS concentration, mean of the upstream and downstream stations

dilution as water with lower levels of TDS enters the stream or to biological activity that results in the removal of nutrient compounds from the water column. There was much less variation between upstream and downstream sampling points in Poore Creek. The concentration of dissolved solids was consistently higher in Poore Creek than in Harrison Creek, though the differences were relatively small except for the seasonal high flow period of late winter - early spring. All of the TDS values were well below the commonly accepted drinking water criterion of 500 mg/l.

The last two water quality parameters are indicators of biological activity in the water column. Biological oxygen demand (BOD) is a test of the rate at which dissolved oxygen is removed from the water by microbial metabolism during a standard 5-day laboratory incubation. Relatively high rates of BOD indicate relatively high levels of input of biodegradable organic matter to the stream. Values as high as 40-50 mg/l are not uncommon during the summer when water temperatures are highest in streams flowing through densely forested ecosystems where there is constant input of organic matter to the stream. Values well above 100 mg/l usually represent pollution by sewage effluents. The BOD values measured in Poore and Harrison Creeks are normal for those type ecosystems (Figures 28-30).

The second of the two biological indicators shows evidence of a serious water quality problem that should be regularly monitored. Coliform bacteria of many different species inhabit the digestive tracts of mammals and contamination of streams with low levels of fecal coliform bacteria is not unusual where wildlife use the streams. However, streamwater is not the preferred habit for coliform bacteria and natural levels are usually low, from 0 several hundred coliform colonies per 100 ml water sample. Both Harrison and Poore Creeks had fecal coliform

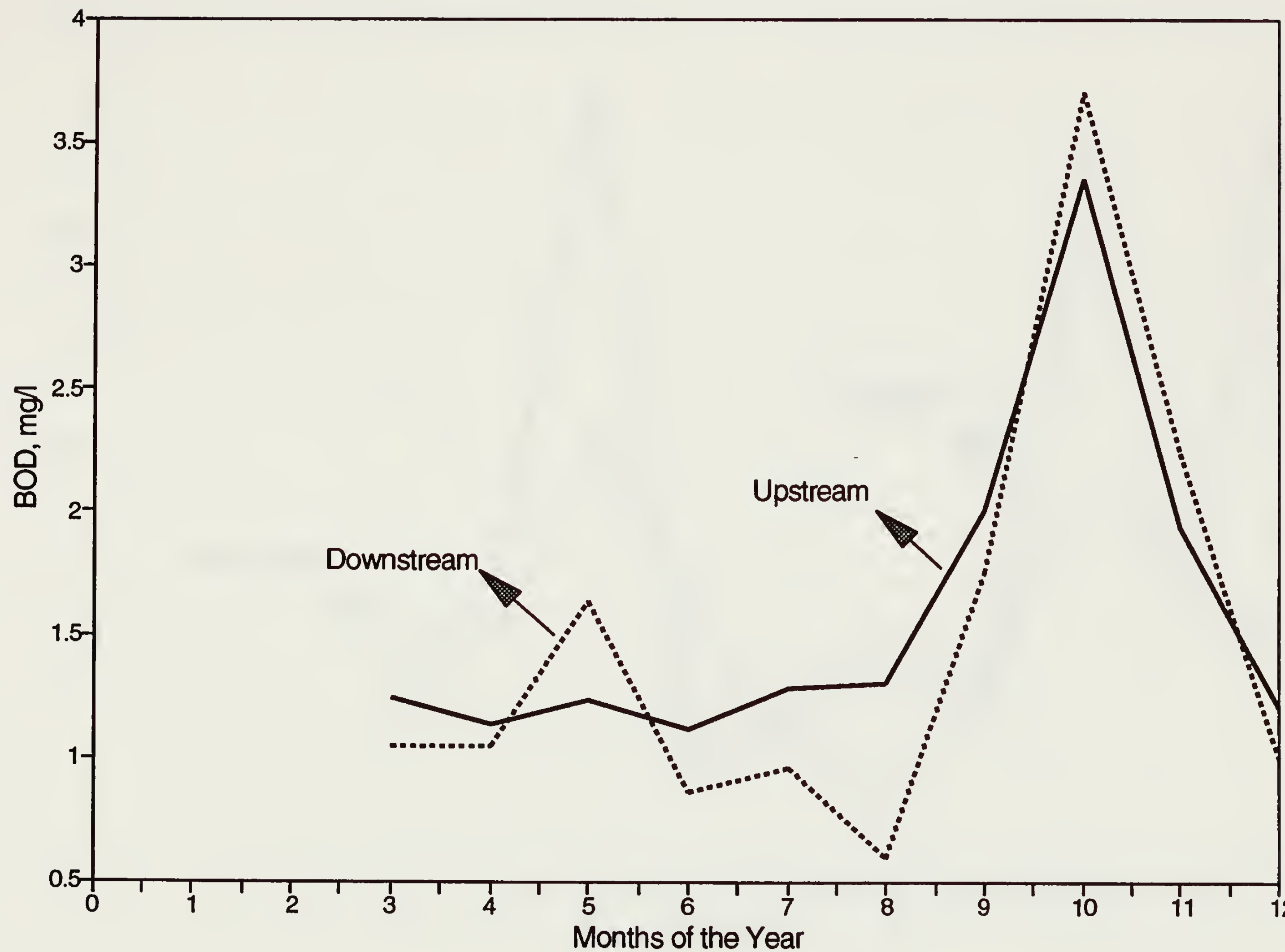

Fig. 28 Mean monthly (1986 - '88) BOD for the Harrison Creek sampling stations

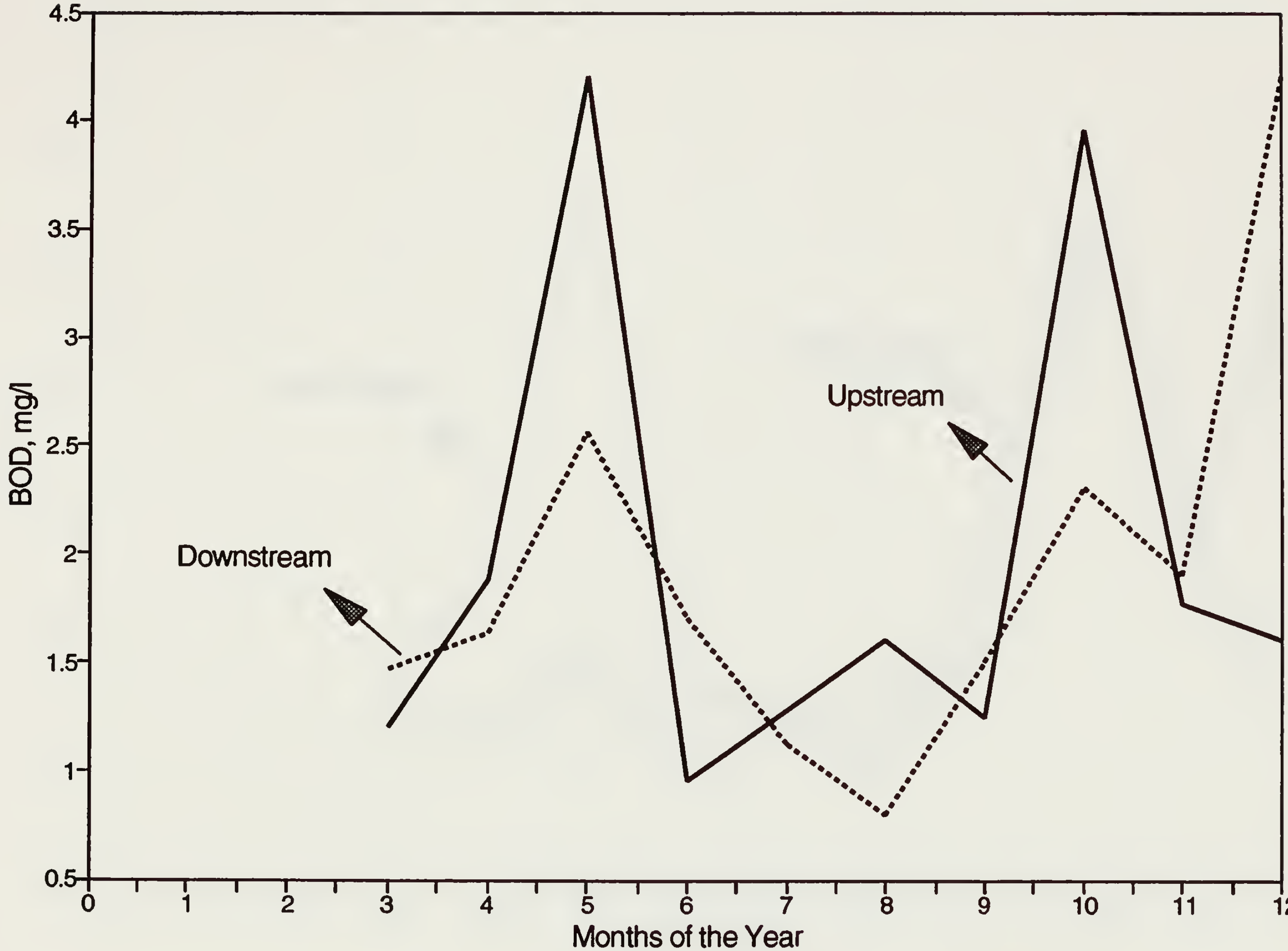

Fig. 29 Mean monthly (1986 - '88) BOD for the Poore Creek sampling stations

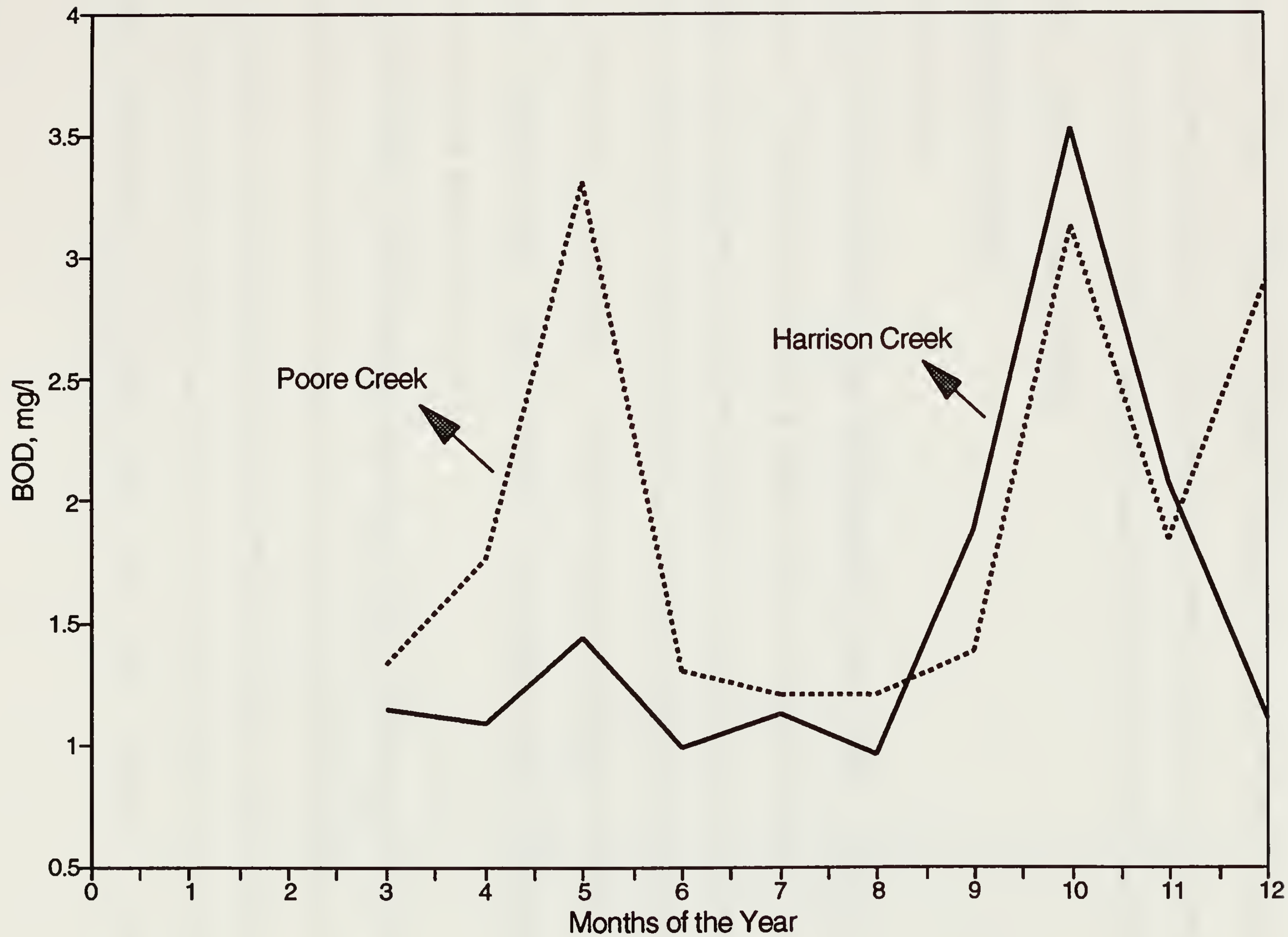

Fig. 30 Mean monthly (1986 - '88) BOD, mean of the upstream and downstream stations

counts at times that were well above recommended levels for recreational waters (Figure 31). Recommendations vary but criteria generally limit counts to 1000-2000/100 ml for such waters. Because there was significant variation among years for fecal coliform levels, monthly means were separated by years. The data of Figure 31 show that fecal coliform levels were elevated well above what are considered to be safe levels for human contact use of the water each summer. But the summer of 1986, in particular, shows strong evidence of continuing extremely high levels - indicative of sewage pollution.

Macroinvertebrate Assessment

1. Harrison Creek

All of the data from Harrison Creek indicate excellent water quality. Species richness ranged from 25-37 species at each sampling station on each sampling date (Table 1), with 39 and 49 species being collected in the creek in February and April, respectively. Forty-three species were collected at H-1, while 46 species were collected at H-2, indicating no difference in water quality between the two stations. Overall, 63 species were found in Harrison Creek over the two sampling periods. Given the extent of the sampling effort, these numbers are typical for unpolluted streams of the vicinity.

The diversity index used incorporates data on both species richness and on the extent of dominance of one or more species in the macroinvertebrate community. High richness, coupled with low dominance, results in a high diversity index, which is indicative of good water quality. Diversity (which is a unitless number) ranged from 3.31 to 4.58 in Harrison Creek (Table 1). These values are relatively high, suggesting excellent water quality. Diversity in unperturbed

streams of this area typically are greater than 3.0; the values noted in Harrison Creek above 4.0 are rather rare for this geographic area.

Table 1. Species richness, mean density (individuals/m^2), and diversity of macroinvertebrates from streams of the Petersburg National Battlefield.

	HARRISON CREEK		POORE CREEK	
	H-1	H-2	P-1	P-2
		<u>February 4, 1987</u>		
Species Richness	25	30	3	7
Diversity	3.72	3.31	1.25	2.48
Mean Density	174	1012	13	86
		<u>April 22, 1987</u>		
Species Richness	36	37	10	15
Diversity	4.07	4.58	2.38	2.58
Mean Density	730	893	197	1132

Macroinvertebrate densities ranged from 174 to 1012 individuals/m^2 (Table 1). Given the sampling technique, and especially the mesh size of the Hess sampler, these densities fall within the range found in clean water steams of the area. The somewhat lower densities noted at H-1 versus H-2 probably are due to the smaller size of the stream channel at H-1 and the lower water velocity, both of which often tend to decrease densities in these streams.

The species composition of the macroinvertebrate community at both sites on Harrison Creek (Tables 2-3) further indicates excellent water quality. Species that are indicators of degraded water quality, such as the Oligochaetes (aquatic worms), <u>Chironomus</u> (midge flies), and various other species, were either present in low densities or not found in the creek. Under conditions of high organic matter inputs to streams, with the usual corresponding low dissolved

oxygen concentrations, these species tend to be very abundant and highly dominant, a situation that does not exist in Harrison Creek.

In addition, the presence of certain species often is indicative of good water quality, especially in terms of low organic matter loading and high oxygen concentrations. The various species of Plecoptera (stoneflies), and to a lesser extent some of the species of Ephemeroptera (mayflies), often are highly sensitive to organic loading. Their presence at both sites indicates good water quality in Harrison Creek.

2. Poore Creek

The data from Poore Creek indicate degraded water quality. Species richness ranged from only 3 to 15 species at either sampling site on either date (Table 1). Only 6 species were collected from Poore Creek in February, while 18 were found in April. Richness was lower at P-1 versus P-2, with 10 versus 16 species being collected at those sites respectively. Only 19 species overall were found in Poore Creek, this being far lower than the 63 species that were collected in Harrison Creek. This rather low species richness suggests relatively poor water quality.

The diversity index ranged from 1.25 to 2.58, with values being lower at P-1 than at P-2 during both sampling periods (Table 1). Diversity was far lower in Poore Creek than in Harrison Creek, and was generally lower than expected values for unperturbed streams in the area. Thus, moderate to poor water quality is indicated by the diversity data, with conditions being worse at P-1.

The densities of macroinvertebrates in Poore Creek were very low in February, ranging from only 13 to 86 individuals/m^2 (Table 1). Although densities increased at P-1 in April, they

still were very low, especially when compared to Harrison Creek. As with the species richness and diversity data, these data also indicated degraded water quality.

The density at P-2 in April, being the highest found at any site or time period, initially may seem somewhat anomalous. However, this high density was the result of a somewhat extensive algal bloom that covered much of the exposed clay substrate at P-2. The macroinvertebrates were responding to both an increase in food resources and cover, hence the much higher density than at any other sampling site.

An examination of the species present in Poore Creek further suggests poor water quality. In February the macroinvertebrate community was dominated by Oligochaetes and the midge fly Chironomus (Table 2), both of which, as noted above, are indicative of organic loading and low oxygen concentrations when they are the dominant organisms present. A similar situation existed at P-1 in April. However, at P-2 in April other species of midge flies were also abundant (Table 3), including Tanytarsus and Dicrotendipes. The high densities of these other species was due to the abundant algal growth in the stream. Species typical of streams with high water quality were noticeably absent.

Table 2. Species list and mean densities (individuals per m^2) of macroinvertebrates collected from Harrison (H) and Poore Creeks (P) on February 4, 1987. Species noted with a + were collected only in the qualitative samples.

	H-1	H-2	P-1	P-2
Annelida				
Oligochaeta	5	16	2	18
Arthropoda				
Amphipoda				
Crangonyx sp.	-	+	-	-
Arachnida				
Hydracarina	-	2	-	-

Copepoda	2	-	-	16
Insecta				
Colembola	-	2	-	-
Ephemeroptera				
Ameletus linearis	+	-	-	-
Baetis sp.	2	-	-	-
Ephemerella sp.	9	-	-	-
Ephemerella inconstans	16	-	-	-
Leptophlebia sp.	-	+	-	-
Plecoptera				
Allocapnia sp.	+	-	-	+
Isoperla bilineata	+	+	-	-
Isoperla clio	-	+	-	-
Plecoptera sp.	-	25	-	-
Trichoptera				
Diplectrona modesta	+	-	-	-
Hydropsyche scalaris	2	2	-	-
Lepidostoma sp.	-	5	-	-
Pycnopsyche sp.	2	5	-	-
Taeniopteryx burski/maura	-	+	-	-
Coleoptera				
Elmidae sp.	2	-	-	-
Diptera				
Chironomus sp.	-	-	9	32
Corynoneura taris	20	177	-	-
Cricotopus sp.	18	170	-	-
Dicrotendipes modestus	2	27	-	-
Diplocladius sp.	34	193	-	2
Hydrobaenus sp.	-	20	-	-
Limnophila sp. 1	7	2	-	-
Limnophila sp. 2	-	2	-	-
Microtendipes pedelus	-	2	-	-
Parametriocnemus	5	2	-	-
Paratendipes sp.	5	9	-	-
Pedicia sp.	-	2	-	-
Pilaria sp.	-	2	-	-
Polypedilum sp.	23	64	-	-

Rheotanytarsus sp.	5	116	-	2
Simulium sp.	2	5	-	-
Tabanus sp.	+	-	-	-
Tanytarsus sp.	11	123	2	16
Thienemanimyia sp. complex	2	39	-	-
Tipula abdominalis	-	+	-	-

Table 3. Species list and mean densities (individuals per m^2) of macroinvertebrates collected from Harrison (H) and Poore Creeks (P) on April 22, 1987. Species noted with a + were collected only in the qualitative samples.

	H-1	H-2	P-1	P-2
Annelida				
Oligochaeta	43	34	23	5
Nematoda	-	7	2	5
Arthropoda				
Amphipoda				
Gammarus sp.	-	2	-	-
Arachnida				
Hydracarina	2	2	2	-
Cladocera	-	-	2	-
Copepoda	30	37	18	41
Insecta				
Colembola	5	-	-	-
Ephemeroptera				
Ameletus linearis	+	-	-	-
Baetis sp.	32	-	-	2
Cloeon alamance	+	-	-	-
Ephemerella inconstans	5	-	-	-
Pseudocloeon sp.	148	80	-	-
Stenonema modestum	+	-	-	-

Plecoptera				
Ampinemoura nigritta	23	64	-	2
Isoperla bilineata	+	2	-	-
Perlesta placida	68	127	-	-
Perlodidae sp.	5	9	-	-
Plecoptera sp.	25	14	5	-
Odonata				
Calopteryx dimidiata	+	-	-	+
Cordulegaster maculata	+	2	-	-
Hemiptera				
Gerris remigis	-	+	-	-
Hespercorixa minor	-	+	-	-
Microvelia americana	+	-	-	-
Trepobates sp.	-	+	-	-
Trichoptera				
Hydropsyche scalaris	2	2	-	-
Taeniopteryx burksi/maura	2	-	-	-
Coleoptera				
Ancyronyx variegata	-	9	-	-
Helichus lithophilus	+	-	-	-
Oulimnius latisculus	2	-	-	-
Uvarus lacustris	+	2	-	-

Diptera				
Chironomidae (pupa)	14	14	2	53
Chironomus sp.	-	-	86	434
Corynoneura taris	2	34	-	-
Cricotopus sp.	-	5	-	-
Dicrotendipes modestus	-	5	39	193
Diplocladius sp.	39	45	18	82
Diptera sp.	-	-	-	2
Hexatoma sp.	23	7	-	-
Hydrobaenus sp.	30	41	-	-
Microtendipes pedelus	-	18	-	-
Parametriocnemus	18	-	-	34
Paratendipes sp.	7	14	-	-
Pilaria sp.	-	2	-	-
Polypedilum sp.	105	93	-	-
Rheotanytarsus sp.	16	50	-	68
Tanytarsus sp.	59	27	-	211
Thienemanimyia sp. complex	34	84	-	-
Tipula abdominalis	+	5	-	+
Zavrelia sp.	18	43	-	-
Ostracoda	-	2	-	-
Mollusca				
Gastropoda				
Physa sp.	-	+	-	-
Pelecypoda				
Psidium sp.	-	11	-	-

There were indications of low water quality in Poore Creek other than the information provided by the macroinvertebrates. The sediments and water had an odor typically found in streams with inputs of sewage. Also, at P-1 there was a relatively abundant growth on the sediments and debris in the stream of the sewage fungus Sphaerotilus natans. This long, stringy, gray-colored bacteria is typically found under conditions of higher organic matter loading. It was also present at P-2, but was less abundant than at P-1 and was not observed at Harrison Creek.

The abundant growth of algae at P-2 in April was due to a species of blue-green algae (Cyanobacteria), suggesting higher concentrations of nutrients (nitrogen and phosphorus) which usually occur along with organic matter inputs, especially from sewage. While the nutrients probably were also present in the creek in February, the colder water temperatures and, in particular, the lower level of light would have inhibited algal growth. The far less abundant algal growth at P-1 versus at P-2 in April was due to there being far less exposed hardpan clay which serves as a stable substrate on which the algae are able to attach. Dense algal growth is far less likely to occur on the shifting sand substrate that is more common at P-1. No such growth was noted in Harrison Creek.

Overall, when the data from Poore Creek are compared with those of Harrison Creek, an obvious indication of degraded water quality in Poore Creek is noted. The shifting sand and hard-pan clay substrates of these streams normally are not ideal as habitat for macroinvertebrates, especially compared with the cobble substrates of Piedmont and mountain streams. Thus, the generally few species and low densities found in these streams was not unexpected.

However, given the similarity of the hydrologic and geomorphologic characteristics of the two streams, it would be expected that their macroinvertebrate communities would be quite similar. Given their differences in species richness, diversity, densities, and dominant indicator organisms, it can be inferred that there was a considerable difference in water quality between the two streams. Further, the relative differences in these parameters, the dominance of Oligochaetes and Chironomus in Poore Creek, and the presence of sewage fungus and dense algal growth all suggest an input of organic matter, most likely in the form of sewage.

All of the data indicate excellent water quality in Harrison Creek. Macroinvertebrate species richness, diversity and density all were typical of relatively unperturbed, clean-water streams of the area. In addition, the species composition of the macroinvertebrate community included species that were typical clean-water indicator organisms.

The data indicated that Poore Creek had far poorer water quality than Harrison Creek and that the source of the problem probably was associated with sewage inputs upstream of the Park boundary. Macroinvertebrate species richness and diversity were much lower than in Harrison Creek. Densities also were lower except where dense blue-green algal growth occurred. This algal growth suggests an input of nutrients to the stream, as would occur with a sewage input. Further, species typical of sewage impacted streams were dominant in Poore Creek, including Oligochaetes (aquatic worms), Chironomus (midge flies) and sewage fungus (Sphaerotilus natans). The impact was greater at the upstream site, no doubt reflecting the closer proximity of that site to the upstream source of the sewage.

Stream Channel Cross-Sections

When the third measurement of stream channel cross-sections was made in February, 1988, 6 of the 30 originally established could not be remeasured because one of the trees used as a reference point had toppled due to bank erosion. Four cross-sections were lost in Poore Creek ;and two were lost in Harrison Creek, leaving a total of 12 in each creek. The cross-section charts are arranged in upstream to downstream order for each creek (Appendix Figures 1-24).

The pattern of variation in the shape of the channel cross-sections between locations on each stream and the pattern of changes in the channel that occurred between measurements at individual locations were typical for small steams - highly variable. The varying erosivity of

different levels of flow and the movement and deposition of sediment results in highly dynamic micromorphology in such channels. However, there is a distinct difference in trends of channel dynamics between the streams when all the cross-sections are categorized according to the net change in the channel between the 1986 and 1988 measurements. In Harrison Creek, there were 4 cross-sections in which there was net erosion or enlargement of the channel cross-section, 3 cross-sections in which there was net aggradation of the channel and there appeared to be no significant net change in the remaining 5 cross-sections except for lateral channel movement. In Poore Creek, there were 7 cross-sections in which there was net erosion, 3 cross-sections in which there was net aggradation and there was no significant net change in the remaining 3 cross-sections.

A major difference between the channels of the two creeks that contributes to differences in erosion rates is channel depth. Poore Creek is much deeper than Harrison Creek, much of the channel has near-vertical sides, and much more of the dense, plastic, samdy clay loam that forms the lower part of the B horizon and the C horizon of the soil is exposed on the sides of the channel than in the Harrison Creek channel. Active erosion of that exposed surface occurs with each large storm in the winter. Freeze-thaw cycles soften the exposed face of the scoured channel of Poore Creek and greatly increase its erodibility. Also, the soil has a weak, blocky structure and the freeze-thaw cycles cause fracture planes to develop. High stormflows erode away the surface layer of softened soil and also large blocks of the soil (as large as 5-6 in across) are loosened and eroded by high flows.

Because significant changes in the micromorphology of the channels occurs with each major storm, it is difficult to assess changes over short periods of time. However, the overall trends

appear to be toward net stability in Harrison Creek and net erosion and channel enlargement in Poore Creek. The impact of increasing development in a watershed may be expressed in increasing channel erosion and channel enlargement over a period of years. The rate at which channel changes will occur depends on the frequency of occurrence of the larger rainfall events that produce high rates of peak stormflow.

CONCLUSIONS AND RECOMMENDATIONS

The evidence presented in this report strongly supports the conclusion that the channel morphology and hydrologic character of Poore Creek in its course through Petersburg National Battlefield has been adversely affected by recent urban development and road construction in the watershed south of the battlefield:

1. Accelerated erosion has been apparent for some years when the channel of Poore Creek is compared to that of Harrison Creek. The Poore Creek channel has been scoured of sediment deposits and bank erosion has been occurring much more frequently and at higher rates along the channel.
2. When historical storm events are compared, stormflow volume and peak flow on an area basis (cfsm) are much greater for Poore Creek than for Harrison Creek.
3. Model predictions indicate that stormfow volume and peak flow on an area basis (cfsm) in Poore Creek for the 10-year 24-hour rainfall event are 12% and 28% greater, respectively, than in Harrison Creek. The current level of development in the Harrison Creek watershed results in 13.5% impervious area and in the Poore Creek watershed results in 28.0% impervious area.
4. Model predictions indicate that actual stormflow volume and peak flow (cfs) in Poore Creek for the 10-year 24-hour rainfall event at the current level of development in the watershed (28.0% impervious area) are 11% and 18% greater, respectively, than when the degree of development was similar to that now seen in the Harrison Creek watershed (13.5% impervious area).
5. Model predictions indicate that for the 10-year 24-hour rainfall event, increasing

development to 28.0% impervious area in the Harrison Creek watershed would increase peak stormflow (cfs) by 17%. Increasing development to 42.5% impervious area in the Poore Creek watershed would increase peak stormflow (cfs) by 16%.

6. The status of macroinvertebrate populations and certain water quality constituents indicate that Poore Creek has sustained significant water quality degradation compared to Harrison Creek. Contamination by sewage effluent was apparent in Poore Creek.

Actions that may be taken to ameliorate the adverse impacts of past upstream development and to prevent further degradation of the ecosystems of Poore and Harrison Creeks are of three main types:

1. Continue monitoring the important hydrologic and water quality parameters of the two streams to build a historical data base and to provide warning of immediate problems such as sewage contamination or increased sediment loads from new construction. We recommend the development of a monitoring plan that includes periodic sampling of both baseflows and stormflows for selected water quality parameters, measuring stormflows of the few largest rainfall events each year, measuring the stream channel cross-sections every 2-3 years, and hiking along the channels periodically to make notes on the conditions of the channels and keep photographic records of key problem areas.
2. Encourage the City of Petersburg to develop and implement a comprehensive stormwater and erosion and sediment control plan for the watersheds of Poore and Harrison Creeks. Adverse hydrologic changes resulting from urbanization can only be effectively controlled by a comprehensive approach that utilizes the wide range of on-site and off-site practices available to control runoff and pollution.

3. Install a detention basin in the channel of each creek. As noted earlier, a rather large basin would be required in each channel to provide effective control of current stormflows and sufficient capacity to control increased stormflows as additional development occurred in the watersheds. A series of smaller detention basins near the outlets of the subbasins is another option that could be considered.

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Appendix Table 1. Watershed land use, areas and curve numbers for Poore Creek - 28.0 % impervious area.

LAND USE, AREA & CURVE NUMBER	SUBWATERSHED NOS. 1	2	3	4	5	TOTAL AREA
Subwatershed Area	172.6	143.8	152.2	94.6	94.8	658.0
Residential Area	7.0	65.0	66.5	9.5	15.0	156.0
Curve Number	80	83	83	83	83	
Industrial Area	1.2		35.6	17.7	7.8	62.2
Curve Number	91		91	91	91	
Roads & Highways	8.0	21.5	13.0	7.9	13.9	64.2
Curve Number	98	98	98	98	98	
Drive & Pathways	1.4	2.2	2.3	0.3		6.3
Curve Number	98	98	98	98		
Open Space	46.6	31.7	27.3	13.4	14.9	134.0
Curve Number	79	79	79	79	79	
Apartment Complex				9.1		9.1
Curve Number				88		
Grassed Area		1.3		8.7	2.2	12.2
Curve Number		70		70	70	
Agricultural Area	16.6					16.6
Curve Number	73					
Compacted Area	10.0	3.7				13.6
Curve Number	87	87				
Water Area	2.4					2.4
Curve Number	100					
Wooded Area	79.4	18.4	7.5	28.0	41.0	174.3
Curve Number	73	73	73	73	73	
Weighted Curve Number	78	83	85	82	81	82

NOTES:

Area in acres, hydrologic soil group C, CN = 80 for residential area with 1/2 acre lots and CN = 83 for area with 1/4 acre lots.

Appendix Table 2. Watershed land use, areas and curve numbers for Poore Creek - 13.5 % impervious area

LAND USE, AREA & CURVE NUMBER	SUBWATERSHED NOS. 1	2	3	4	5	TOTAL AREA
Subwatershed Area	172.6	143.8	152.2	94.6	94.8	658.0
Residential Area	7.0	25.5	30.0	9.5	3.0	75.0
Curve Number	80	80	80	80	80	
Industrial Area	1.2		10.0		7.8	19.0
Curve Number	91		91	91	91	
Roads & Highways	8.0	18.0	9.0	6.0	10.0	51.0
Curve Number	98	98	98	98	98	
Drive & Pathways	1.4	1.8	1.9	0.3		5.4
Curve Number	98	98	98	98		
Open Space	46.6	31.7	40.0	25.0	23.9	167.2
Curve Number	79	79	79	79	79	
Apartment Complex						
Curve Number						
Grassed Area		1.3		8.7	2.2	12.2
Curve Number		70		70	70	
Agricultural Area	16.6	6.2	13.7	5.0	6.9	48.4
Curve Number	73	73	73	73	73	
Compacted Area	10.0	3.7				13.6
Curve Number	87	87				
Water Area	2.4					2.4
Curve Number	100					
Wooded Area	79.4	55.6	47.6	40.1	41.0	263.7
Curve Number	73	73	73	73	73	
Weighted Curve Number	78	79	79	77	79	78

NOTES:

Area in acres, hydrologic soil group C, residential area with 1/2 acre lots.

Appendix Table 3. Watershed land use, areas and curve numbers for Poore Creek - 42.5 % impervious area

LAND USE, AREA & CURVE NUMBER	SUBWATERSHED NOS. 1	2	3	4	5	TOTAL AREA
Subwatershed Area	172.6	143.8	152.2	94.6	94.8	658.0
Residential Area	70.0	65.0	66.5	28.0	15.0	244.5
Curve Number	83	83	83	83	83	
Industrial Area	32.0	15.0	35.6	17.7	25.0	125.3
Curve Number	91	91	91	91	91	
Roads & Highways	22.6	21.5	13.0	10.0	15.0	82.1
Curve Number	98	98	98	98	98	
Drive & Pathways	3.5	2.2	2.3	1.5	1.0	10.5
Curve Number	98	98	98	98	98	
Open Space	7.7	16.7	17.3	7.6	14.9	64.3
Curve Number	79	79	79	79	79	
Apartment Complex	10.0	3.0	10.0	9.1	13.0	45.1
Curve Number	88	88	88	88	88	
Grassed Area		1.3		8.7	2.2	12.2
Curve Number		70		70	70	
Agricultural Area						
Curve Number						
Compacted Area	10.0	3.7				13.6
Curve Number	87	87				
Water Area	2.4					2.4
Curve Number	100					
Wooded Area	14.4	15.4	7.5	12.0	9.7	59.0
Curve Number	73	73	73	73	73	
Weighted Curve Number	86	85	86	84	87	86

NOTES:

Area in acres, hydrologic soil group C and residential area with 1/4 acre lots.

Appendix Table 4. Watershed land use, areas and curve numbers for Harrison Creek - 13.5 % impervious area

LAND USE, AREA & CURVE NUMBER	SUBWATERSHED NOS. 1	2	3	4	TOTAL AREA
Subwatershed Area	124.0	130.5	80.0	101.5	436.0
Residential Area	38.0	6.0	9.0	13.0	66.0
Curve Number	80	80	80	80	
Industrial Area					
Curve Number					
Roads & Highways	5.9	4.5	4.3	5.5	20.2
Curve Number	98	98	98	98	
Drive & Pathways	1.9		2.6	4.7	9.2
Curve Number	98		98	98	
Open Space	25.0	10.0	23.2	33.7	91.8
Curve Number	79	79	79	79	
Parking Lots	0.8			3.9	4.7
Curve Number	98			98	
Grassed Area	5.8	1.5	0.4	17.3	24.9
Curve Number	70	70	70	70	
Agricultural Area		16.6	5.0	3.5	25.0
Curve Number		73	73	73	
Compacted Area		0.6	1.0	0.1	1.7
Curve Number		87	87	87	
Water Area		1.0	0.8		1.8
Curve Number		100	100		
Wooded Area	46.7	90.3	33.9	19.8	190.7
Curve Number	73	73	73	73	
Weighted Curve Number	78	75	78	79	77

NOTES:

Area in acres, hydrologic soil group C and residential area with 1/2 acre lots.

Appendix Table 5. Watershed land use, areas and curve numbers for Harrison Creek - 28.0 % impervious area

LAND USE, AREA & CURVE NUMBER	SUBWATERSHED NOS. 1	2	3	4	TOTAL AREA
Subwatershed Area	124.0	130.5	80.0	101.5	436.0
Residential Area	48.0	20.0	15.0	25.0	108.0
Curve Number	83	83	83	83	
Industrial Area		23.0	12.0	10.0	45.0
Curve Number		91	91	91	
Roads & Highways	7.0	9.0	7.0	8.0	31.0
Curve Number	98	98	98	98	
Drive & Pathways	2.5	1.5	2.6	5.4	12.0
Curve Number	98	98	98	98	
Open Space	22.0	16.0	28.1	25.7	91.8
Curve Number	79	79	79	79	
Apartment Complex	3.0	3.0		5.0	11.0
Curve Number	88	88	88	88	
Grassed Area	5.8	1.5	0.4	7.3	14.9
Curve Number	70	70	70	70	
Agricultural Area		14.6			14.6
Curve Number		73			
Compacted Area		0.6	1.0	0.1	1.7
Curve Number		87	87	87	
Water Area		1.0	0.8		1.8
Curve Number		100	100		
Wooded Area	35.7	40.3	13.2	15.0	104.2
Curve Number	73	73	73	73	
Weighted Curve Number	80	81	83	83	82

NOTES:

Area in acres, hydrologic soil group C and residential area with 1/4 acre lots.

Appendix Table 6. Watershed parameters for Poore Creek - 28.0 % impervious area

SUBWATERSHED PARAMETERS	SUBWATERSHED NOS. 1	2	3	4	5
Subwatershed Area acres	172.6	143.8	152.2	94.6	94.8
Longest Stream Length, Z, ft	4800.0	3600.0	3200.0	2400.0	2400.0
Upper Elevation E1, ft	145.0	150.0	155.0	155.0	140.0
Lower Elevation E2, ft	80.0	85.0	98.0	98.0	80.0
Subwatershed Slope Y %	1.4	1.8	1.8	2.4	2.5
SCS Runoff Curve Number, CN	77	83	85	82	81
Potential Storage S	3.0	2.0	1.8	2.2	2.3
SCS Lag Time L, hr	1.0	0.6	0.5	0.4	0.4
Time of Concentration, Tc, hr	1.8	1.0	0.9	0.7	0.7
Flow Length to Outlet, X, ft	0.0	0.0	2000.0	2000.0	0.0
Manning Flow velocity, ft/sec	0.0	0.0	3.5	3.5	0.0
Travel Time to Outlet, Tt, hr			0.2	0.2	
Cumulative Travel Time, T, hr	0.0	0.0	0.2	0.2	0.0

Appendix Table 7. Watershed parameters for Poore Creek - 13.5 % impervious area

SUBWATERSHED PARAMETERS	SUBWATERSHED NOS. 1	2	3	4	5
Subwatershed Area acres	172.6	143.8	152.2	94.6	94.8
Longest Stream Length, Z, ft	4800.0	3600.0	3200.0	2400.0	2400.0
Upper Elevation E1, ft	145.0	150.0	155.0	155.0	140.0
Lower Elevation E2, ft	80.0	85.0	98.0	98.0	80.0
Subwatershed Slope Y %	1.4	1.8	1.8	2.4	2.5
SCS Runoff Curve Number, CN	77	79	79	77	79
Potential Storage S	3.0	2.7	2.7	3.0	2.7
SCS Lag Time L, hr	1.0	0.7	0.6	0.5	0.4
Time of Concen-tration, Tc, hr	1.8	1.1	1.0	0.8	0.7
Flow Length to Outlet, X, ft	0.0	0.0	2000.0	2000.0	0.0
Manning Flow velocity, ft/sec	0.0	0.0	3.5	3.5	0.0
Travel Time to Outlet, Tt, hr			0.2	0.2	
Cumulative Travel Time, T, hr	0.0	0.0	0.2	0.2	0.0

Appendix Table 8. Watershed parameters for Poore Creek - 42.5 % impervious area

SUBWATERSHED PARAMETERS	SUBWATERSHED NOS. 1	2	3	4	5
Subwatershed Area acres	172.6	143.8	152.2	94.6	94.8
Longest Stream Length, Z, ft	4800.0	3600.0	3200.0	2400.0	2400.0
Upper Elevation E1, ft	145.0	150.0	155.0	155.0	140.0
Lower Elevation E2, ft	80.0	85.0	98.0	98.0	80.0
Subwatershed Slope Y %	1.4	1.8	1.8	2.4	2.5
SCS Runoff Curve Number, CN	86	85	86	84	87
Potential Storage S	1.6	1.8	1.6	1.9	1.5
SCS Lag Time L, hr	0.8	0.6	0.5	0.4	0.3
Time of Concen-tration, Tc, hr	1.3	0.9	0.8	0.6	0.5
Flow Length to Outlet, X, ft	0.0	0.0	2000.0	2000.0	0.0
Manning Flow velocity, ft/sec	0.0	0.0	3.5	3.5	0.0
Travel Time to Outlet, Tt, hr			0.2	0.2	
Cumulative Travel Time, T, hr	0.0	0.0	0.2	0.2	0.0

Appendix Table 9. Watershed parameters for Harrison Creek - 28.0 % impervious area

SUBWATERSHED PARAMETERS	SUBWATERSHED NOS. 1	2	3	4
Subwatershed Area acres	124.0	130.5	80.0	101.5
Longest Stream Length Z, ft	4500.0	3750.0	4000.0	3680.0
Upper Elevation E1, ft	152.0	158.0	152.0	150.0
Lower Elevation E2, ft	90.0	102.0	90.0	92.0
Subwatershed Slope Y %	1.4	1.5	1.6	1.6
SCS Runoff Curve Number CN	80	75	78	79
Potential Storage S	2.5	3.3	2.8	2.7
SCS Lag Time L, hr	0.9	0.9	0.8	0.7
Time of Concentration Tc, hr	1.5	1.5	1.4	1.2
Flow Length to Outlet X, ft	0.0	1400.0	0.0	900.0
Manning Flow Velocity ft/sec		1.3		1.3
Travel Time to Outlet Tt, hr		0.3		0.2
Cumulative Travel Time T, hr	0.0	0.3	0.0	0.2

Appendix Table 10. Watershed parameters for Harrison Creek - 13.5 % impervious area

SUBWATERSHED PARAMETERS	SUBWATERSHED NOS. 1	2	3	4
Subwatershed Area acres	124.0	130.5	80.0	101.5
Longest Stream Length Z, ft	4500.0	3750.0	4000.0	3680.0
Upper Elevation E1, ft	152.0	158.0	152.0	150.0
Lower Elevation E2, ft	90.0	102.0	90.0	92.0
Subwatershed Slope Y %	1.4	1.5	1.6	1.6
SCS Runoff Curve Number CN	80	81	83	83
Potential Storage S	2.5	2.3	2.0	2.0
SCS Lag Time L, hr	0.9	0.7	0.7	0.7
Time of Concentration Tc, hr	1.5	1.2	1.2	1.1
Flow Length to Outlet X, ft	0.0	1400.0	0.0	900.0
Manning Flow Velocity ft/sec		1.3		1.3
Travel Time to Outlet Tt, hr		0.3		0.2
Cumulative Travel Time T, hr	0.0	0.3	0.0	0.2

Appendix Table 11. Approximate values of rainfall depth-duration for storms of different return periods, Petersburg, VA.

Duration	Storms of return periods						
	1-yr in	2-yr in	5-yr in	10-yr in	25-yr in	50-yr in	100-yr in
5 min		0.475	0.545	0.6	0.681	0.746	0.81
15 min		0.97	1.16	1.298	1.502	1.661	1.82
30 min	1.17	1.48	1.9	2.18	2.42	2.88	3.02
1 hr	1.5	1.9	2.3	2.7	3.21	3.6	4
2 hr	1.78	2.1	2.7	3.2	3.7	4.1	4.51
3 hr	1.84	2.3	2.9	3.5	4	4.5	5
6 hr	2.25	2.8	3.5	4.1	4.8	5.5	6
12 hr	2.75	3.32	4	4.87	5.7	6.3	7
24 hr	2.9	3.5	4.7	5.7	6.3	7.1	7.9

Note: Values were approximated from published charts of rainfall depth-duration-frequency curves (Frederick, et al., 1977).

Appendix Table 12. Approximate values of rainfall intensity-duration for storms of different return periods, Petersburg, VA.

Duration	Storms of return periods						
	1-yr in/hr	2-yr in/hr	5-yr in/hr	10-yr in/hr	25-yr in/hr	50-yr in/hr	100-yr in/hr
5 min		5.7	6.54	7.2	8.172	8.952	9.72
15 min		3.88	4.64	5.192	6.008	6.644	7.28
30 min	2.34	2.96	3.8	4.36	4.84	5.76	6.04
1 hr	1.5	1.9	2.3	2.7	3.21	3.6	4
2 hr	0.89	1.05	1.35	1.6	1.85	2.05	2.255
3 hr	0.613	0.767	0.967	1.167	1.333	1.500	1.667
6 hr	0.375	0.467	0.583	0.683	0.800	0.917	1.000
12 hr	0.229	0.277	0.333	0.406	0.475	0.525	0.583
24 hr	0.121	0.146	0.196	0.238	0.263	0.296	0.329

Note: Values were computed based on approximate rainfall depth-duration values from appendix Table 11.

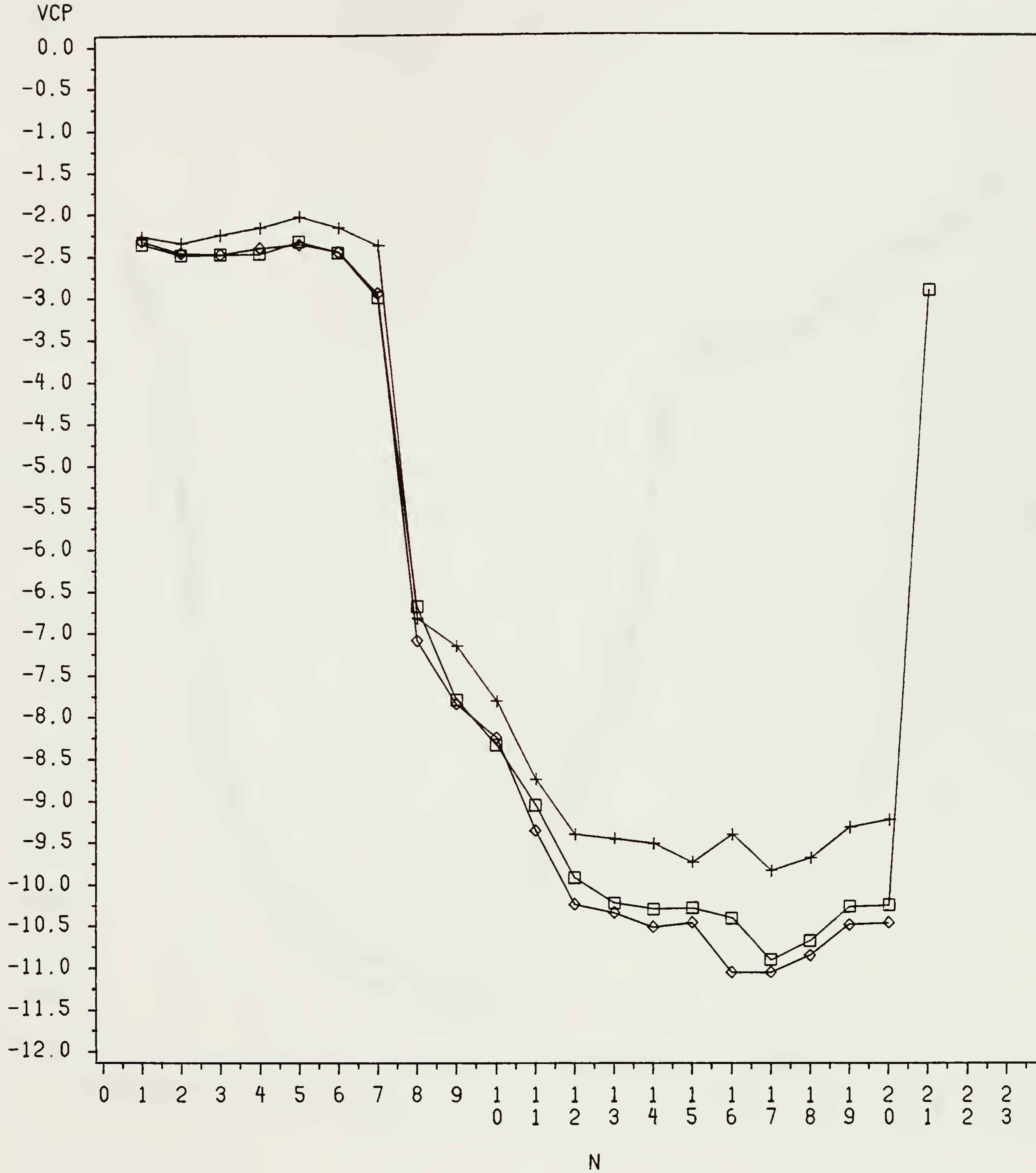
Appendix Table 13. Parameters for discharges estimated by the Rational Formula for Poore Creek & Harrison Creek for existing conditions

Watershed Name	Watershed Area acres	Runoff Coefficient	Percent Impervious area %	Time of Concentration min	Frequency of Return Period 10-yr Rain Intens. in/hr	Peak Disch. cfs	25-yr Rain Intens. in/hr	Peak Disch. cfs	50-yr Rain Intens. in/hr	Peak Disch. cfs	100-yr Rain Intens. in/hr	Peak Disch. cfs
POORE CREEK	658	0.46	28.0	32	4.15	1256	4.85	1468	5.55	1680	5.95	1801
HARRISON CREEK	436	0.32	13.5	30	4.25	597	4.95	695	5.7	800	6.15	863

Notes:

1. Runoff coefficient represents the composite or weighted average for the whole watershed.
2. Percent impervious area represents the net value of impervious area in the whole watershed.
3. Time of concentration is calculated by Kirpich's equation.

POORE CREEK CROSS SECTION
PCVC39



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GOING DOWNSTREAM
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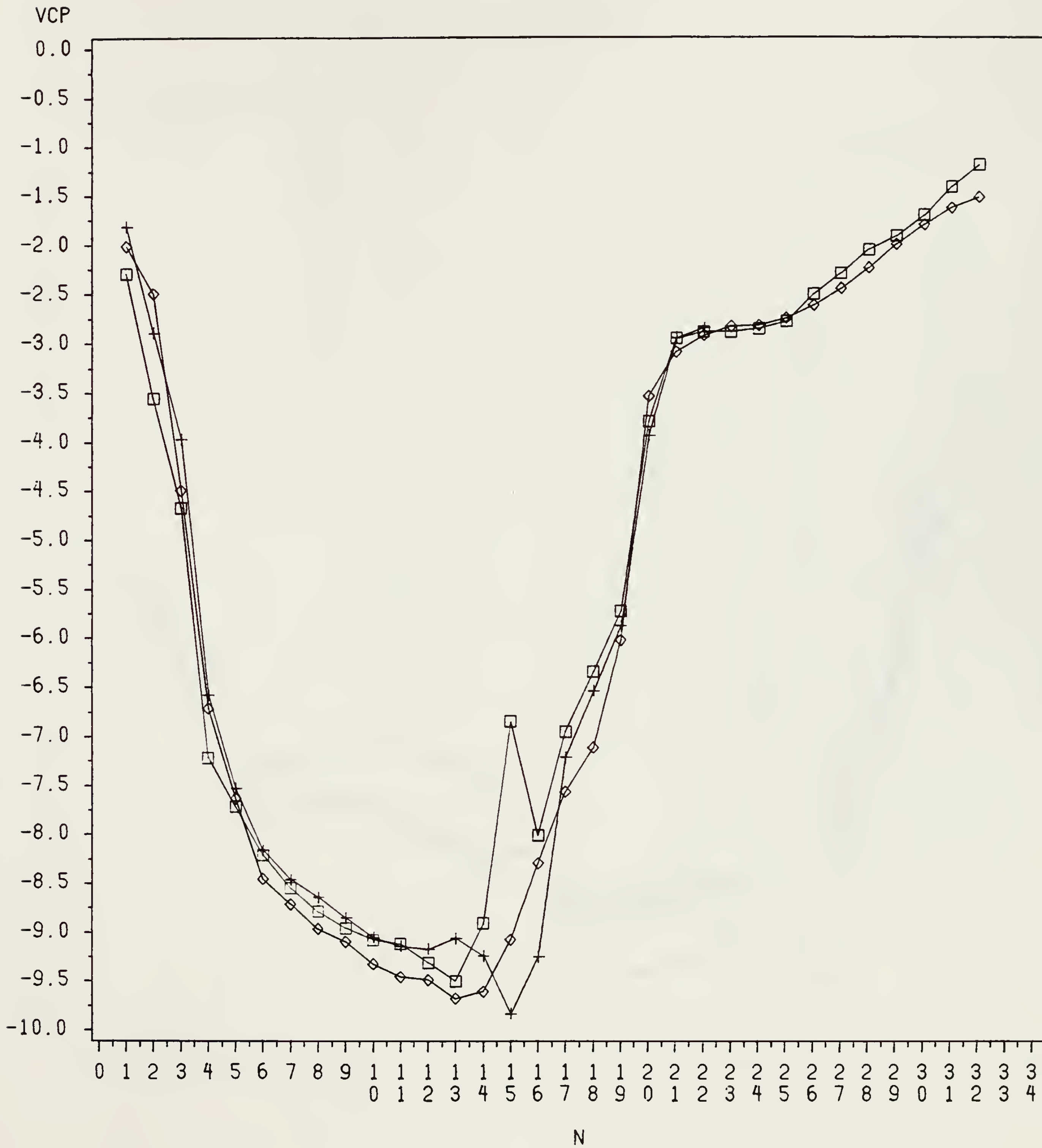
DIAMOND=FEBRUARY 1987
SQUARE=FEBRUARY 1988

POORE CREEK CROSS SECTION
PCVC38



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POORE CREEK CROSS SECTION
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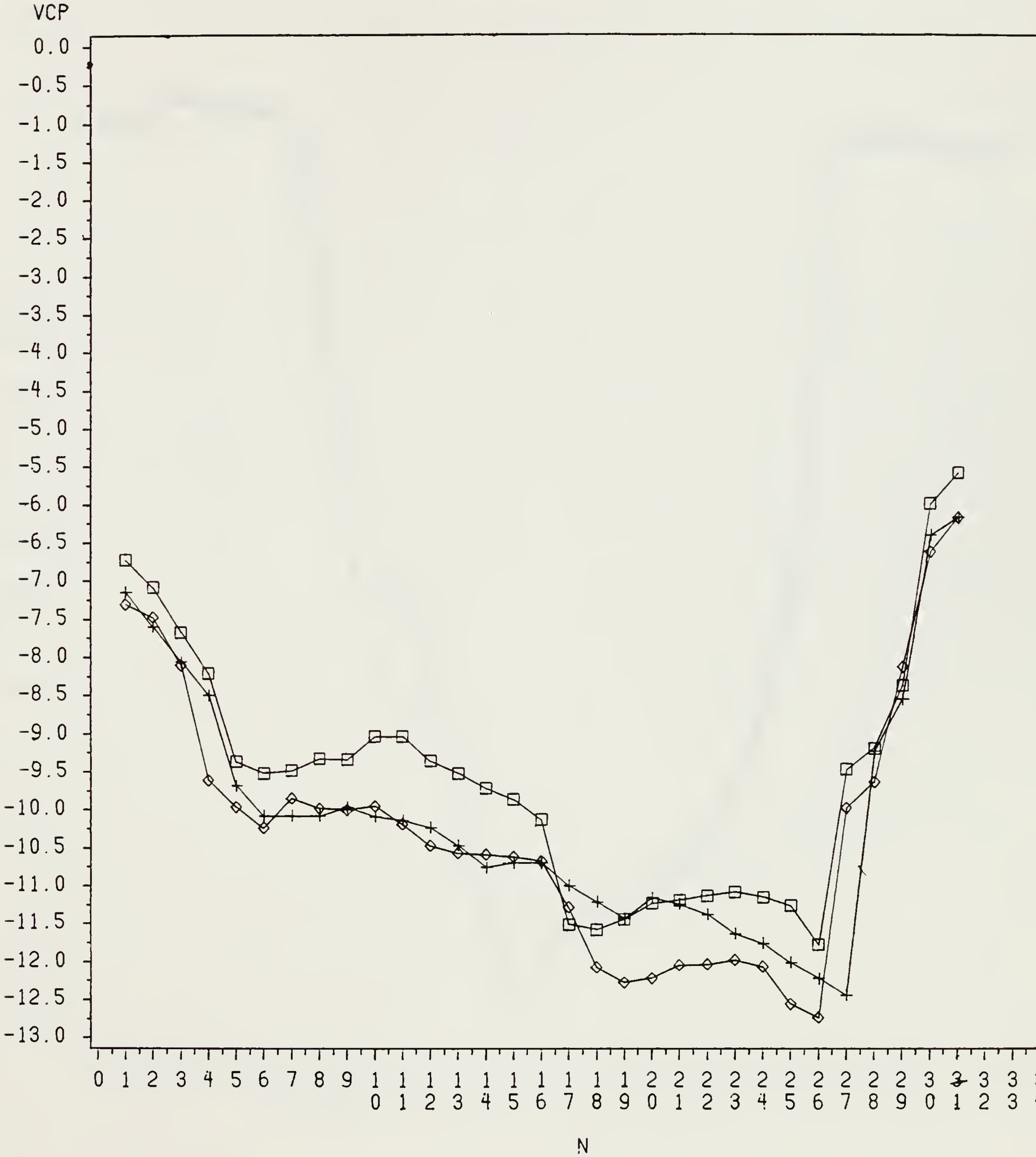

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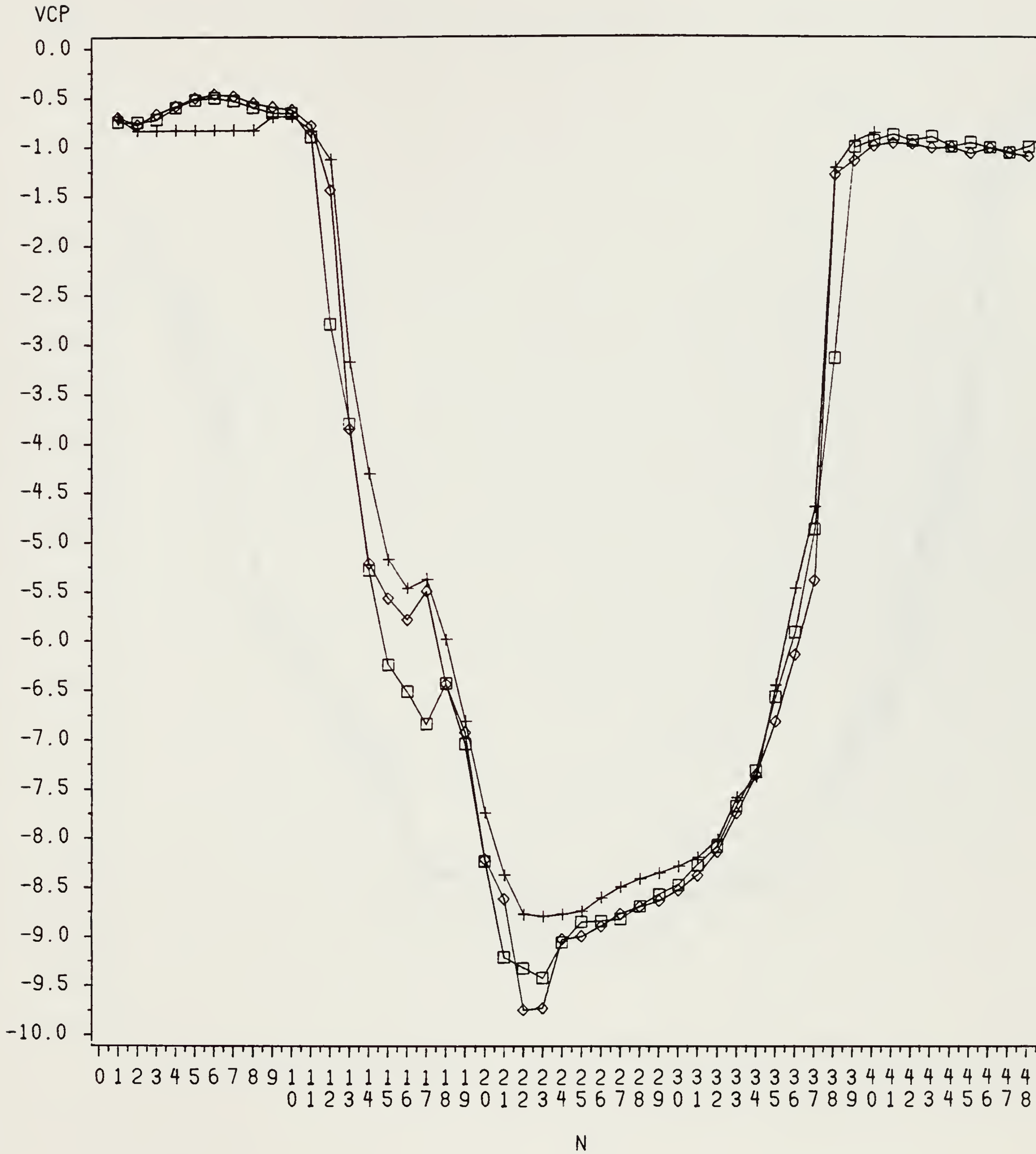
POORE CREEK CROSS SECTION
PCVC36



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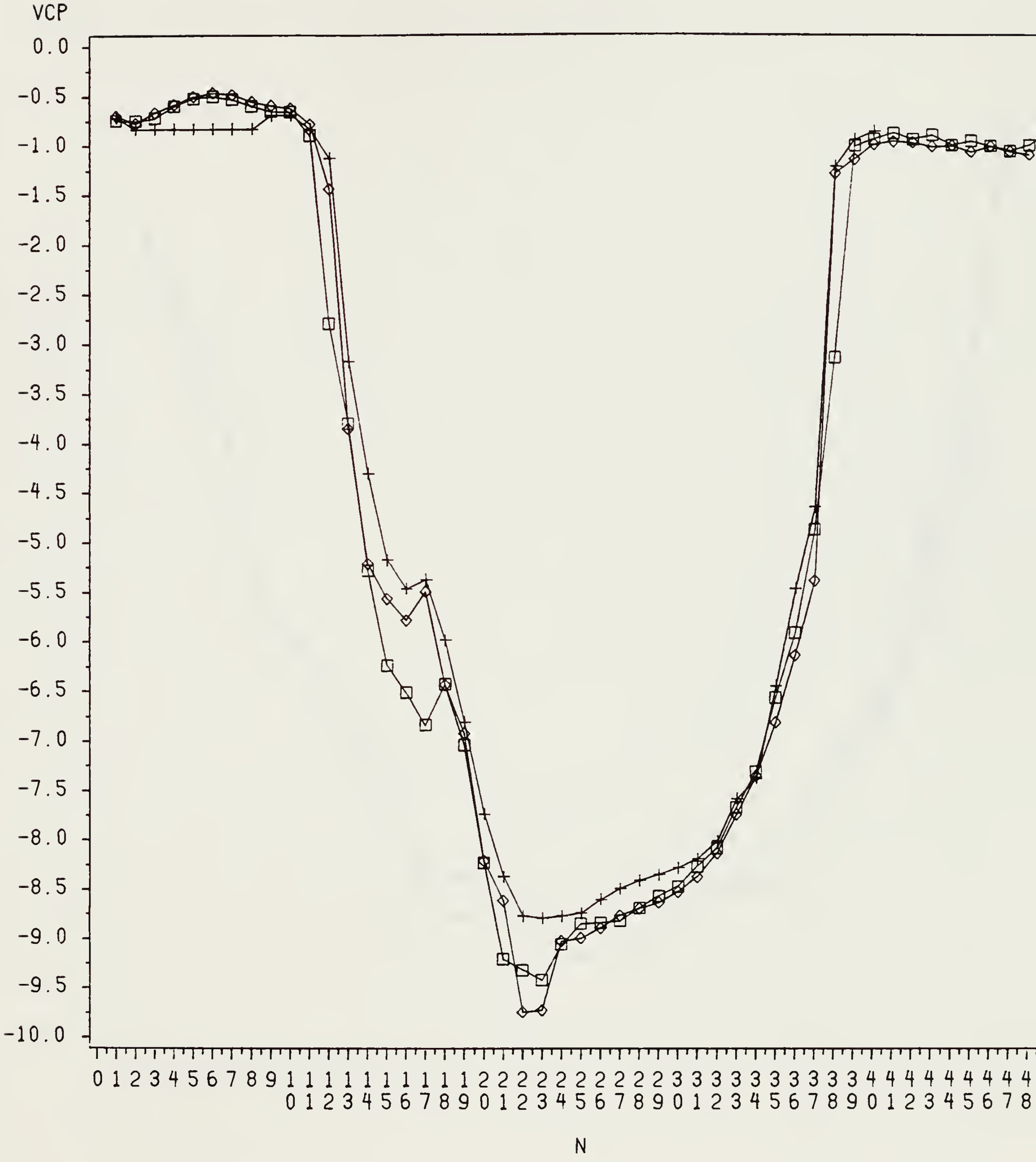
POORE CREEK CROSS SECTION
PCVC36



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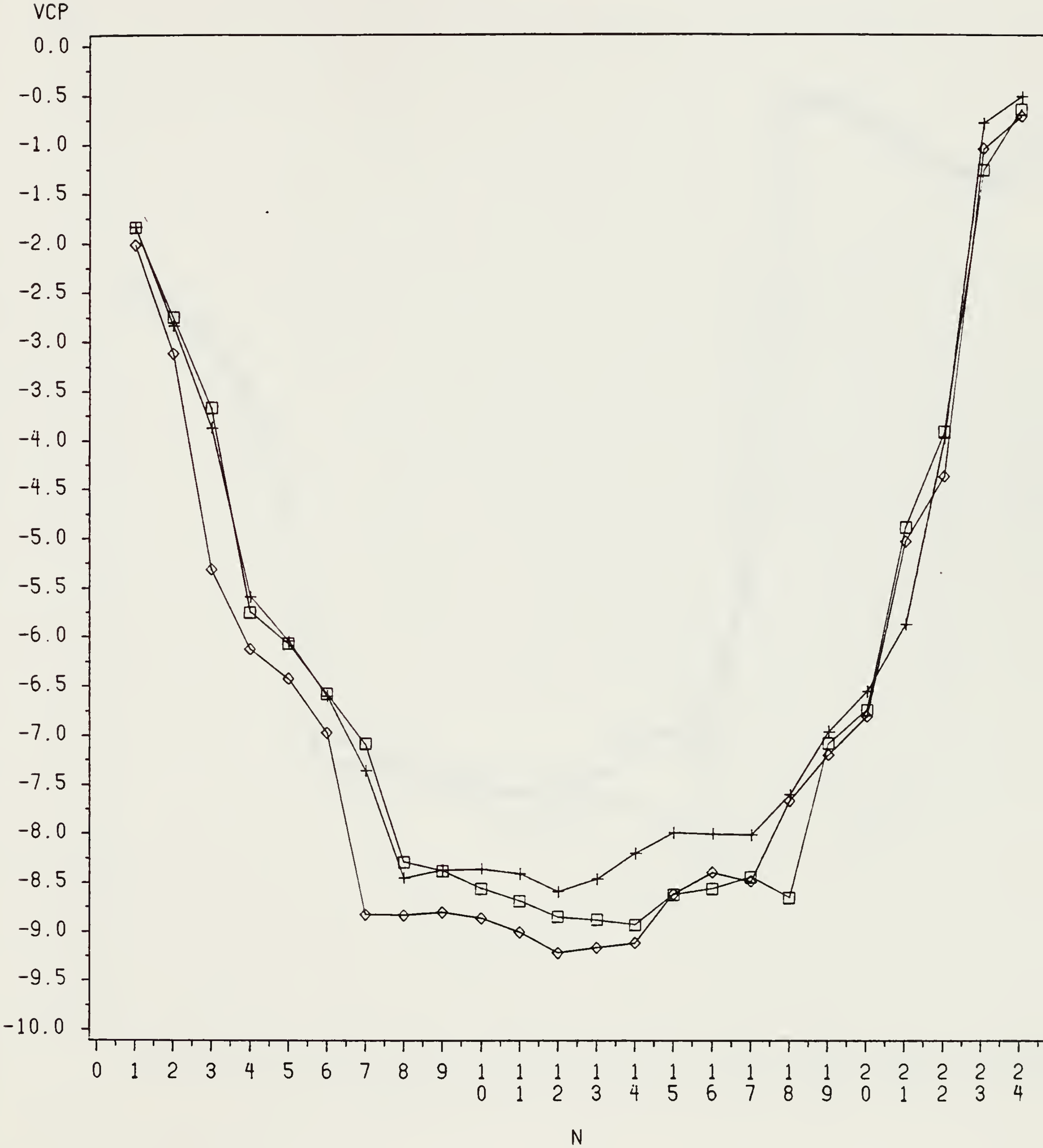
POORE CREEK CROSS SECTION
PCC15



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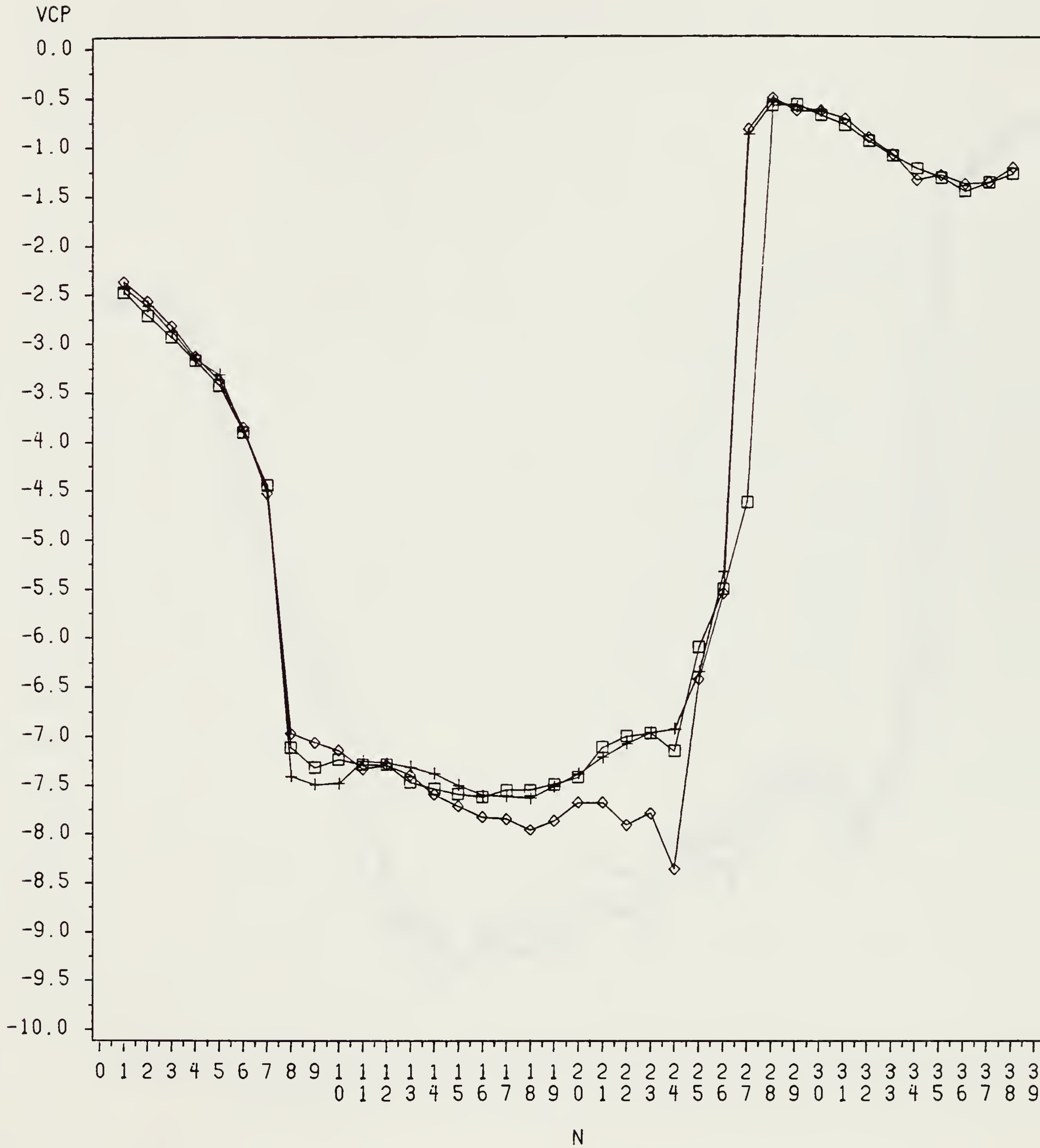
POORE CREEK CROSS SECTION PCVC34



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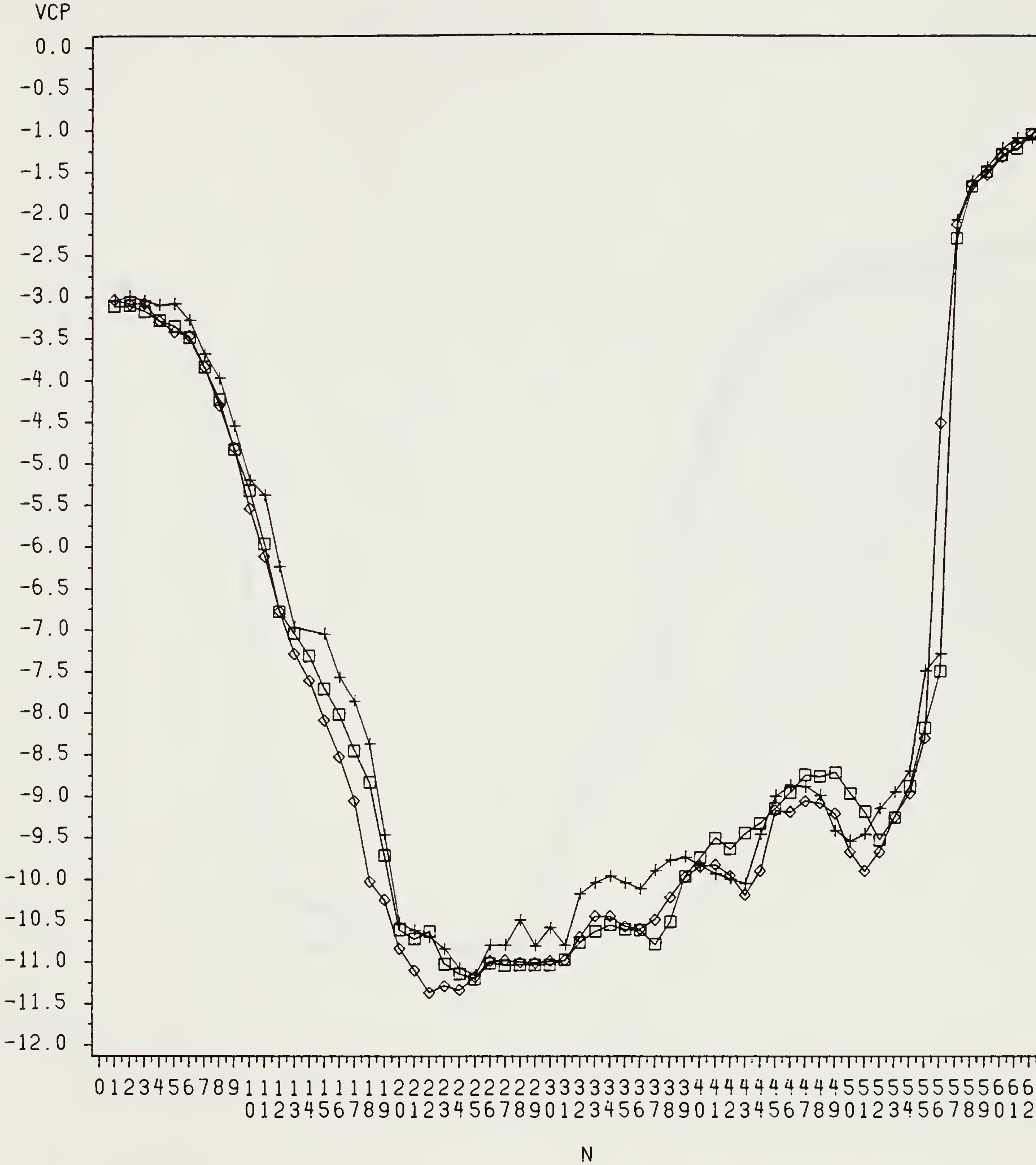
POORE CREEK CROSS SECTION
PCVC33



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POORE CREEK CROSS SECTION
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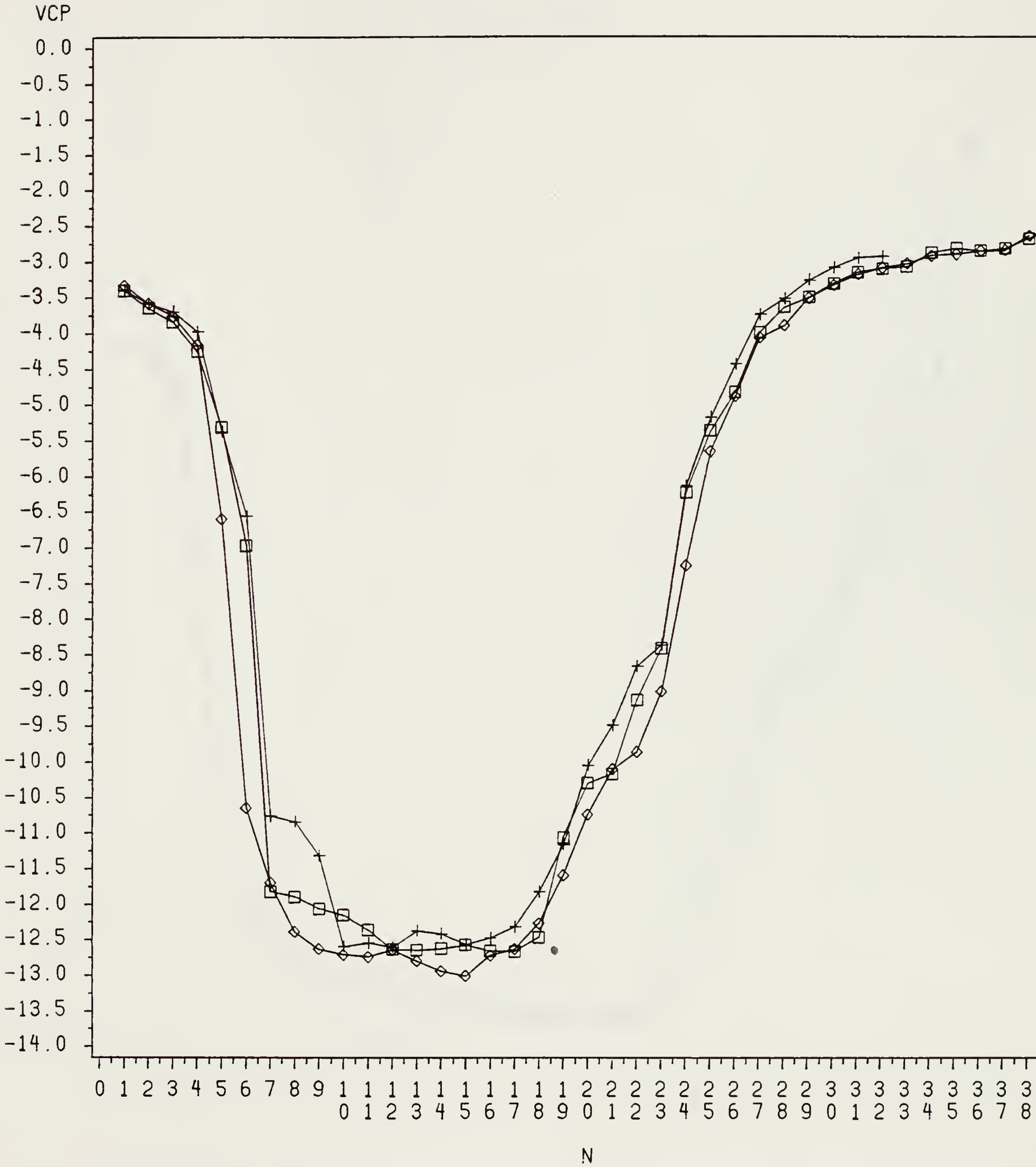

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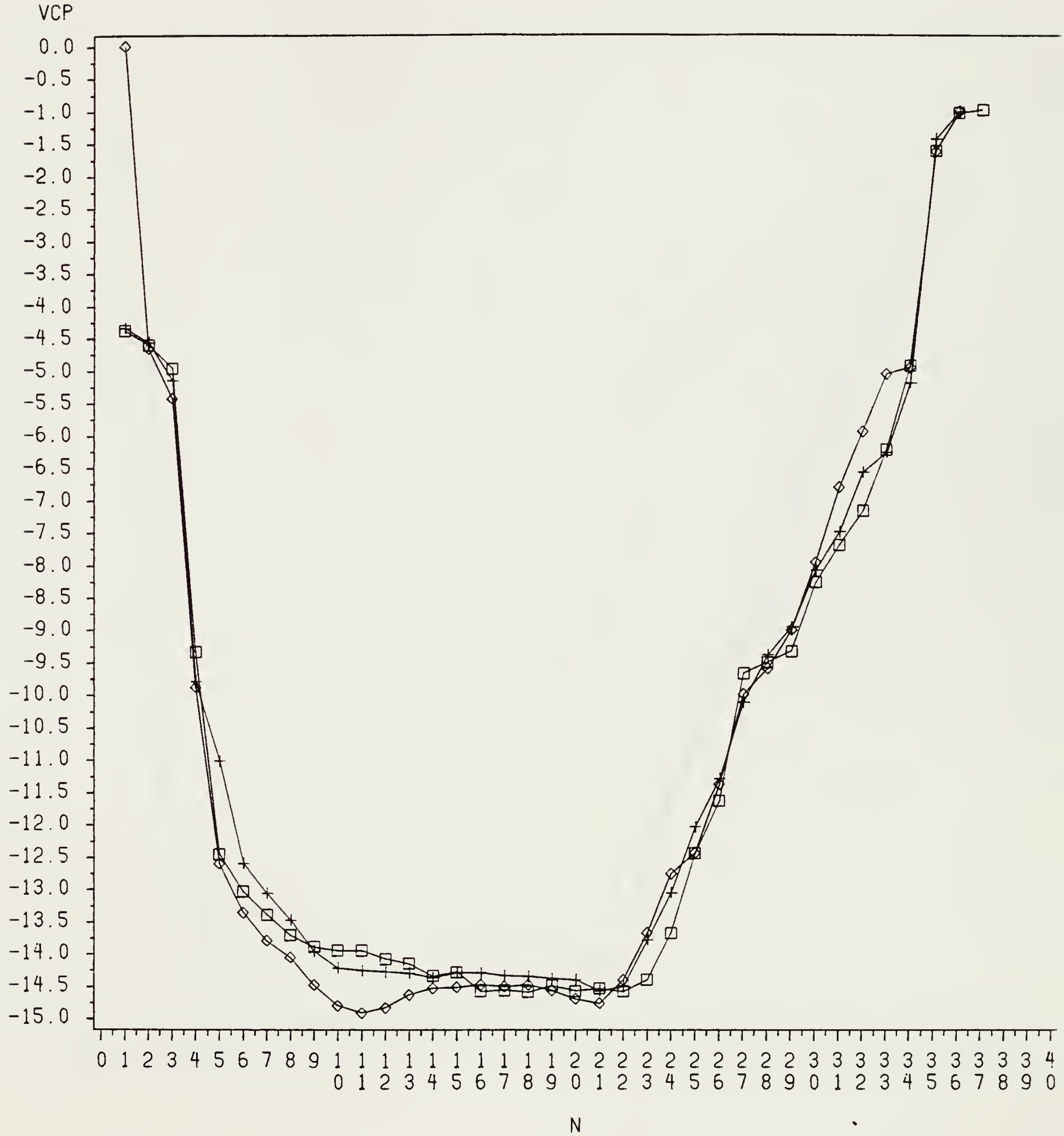
POORE CREEK CROSS SECTION
PCVC31



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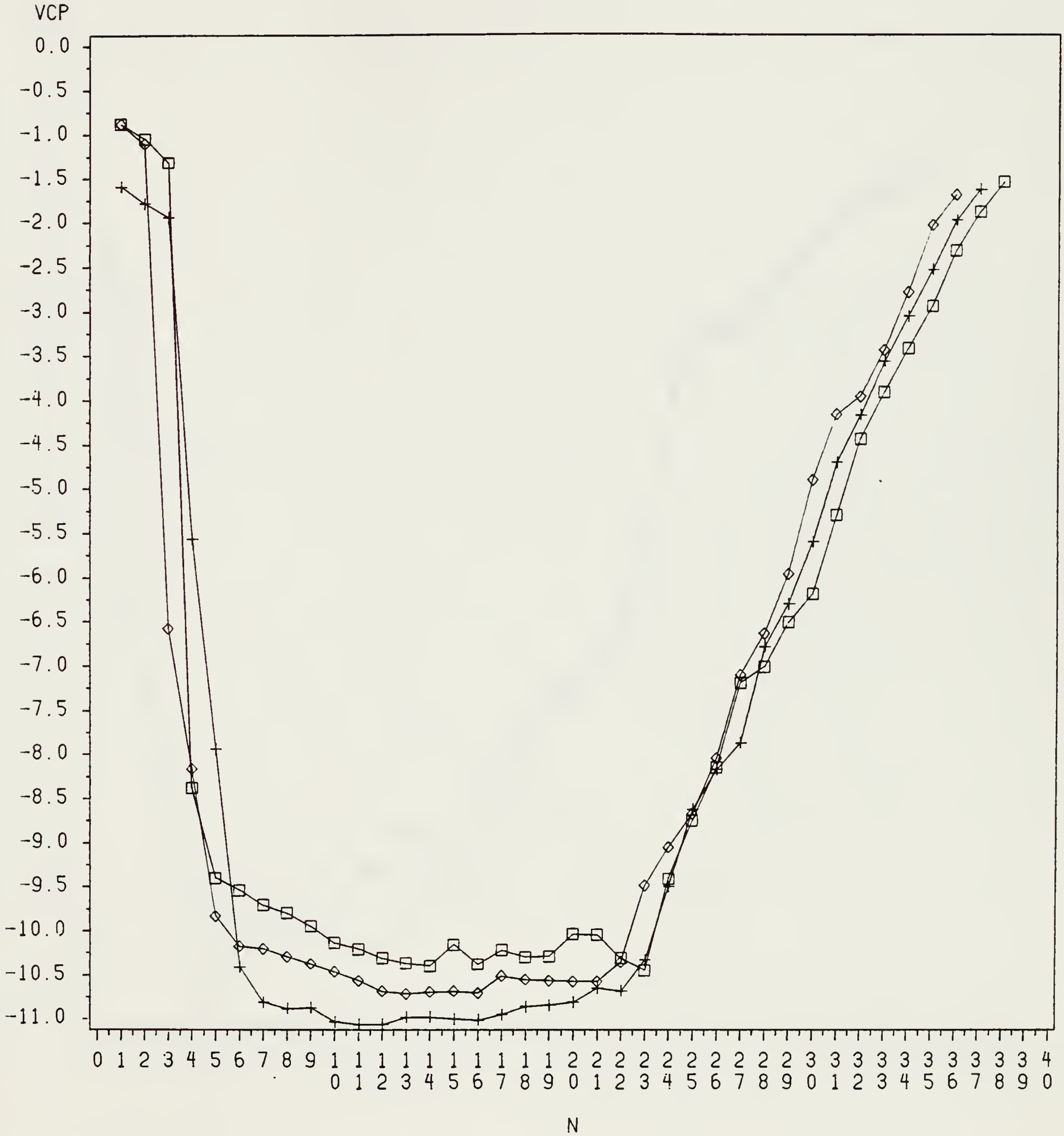
POORE CREEK CROSS SECTION
PCVC29



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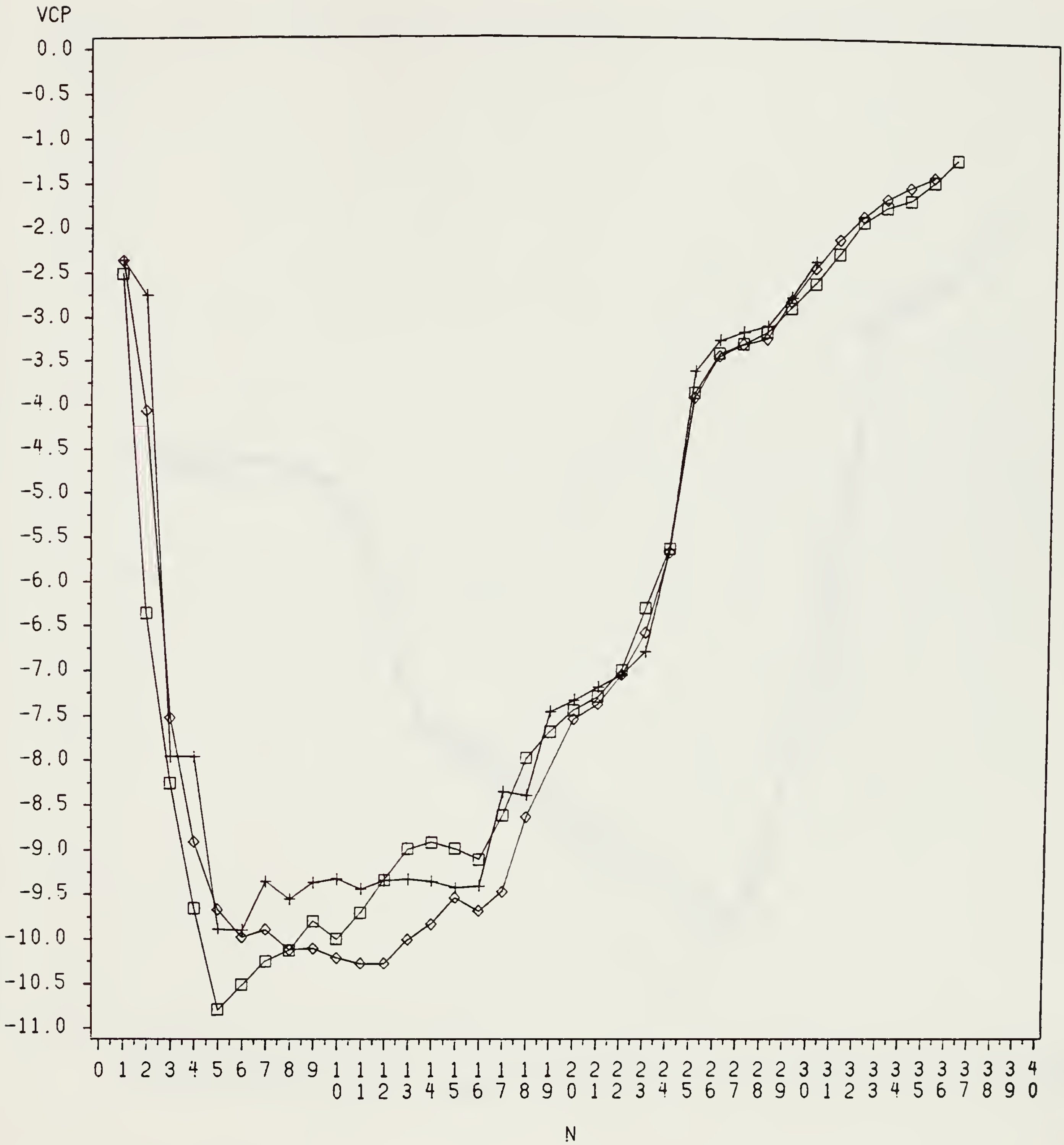
POORE CREEK CROSS SECTION
PCVC21



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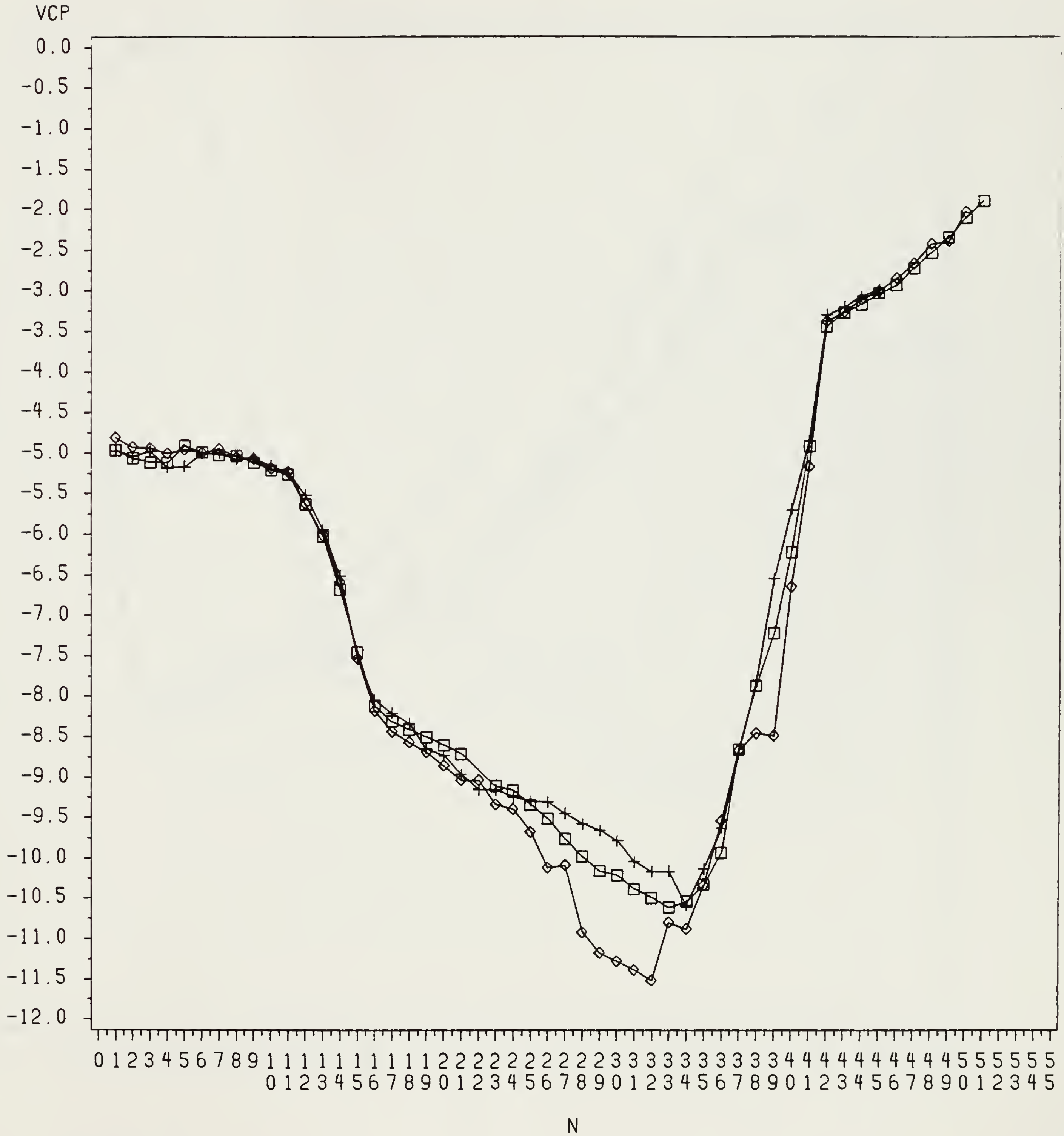
POORE CREEK CROSS SECTION
PCVC12

✓



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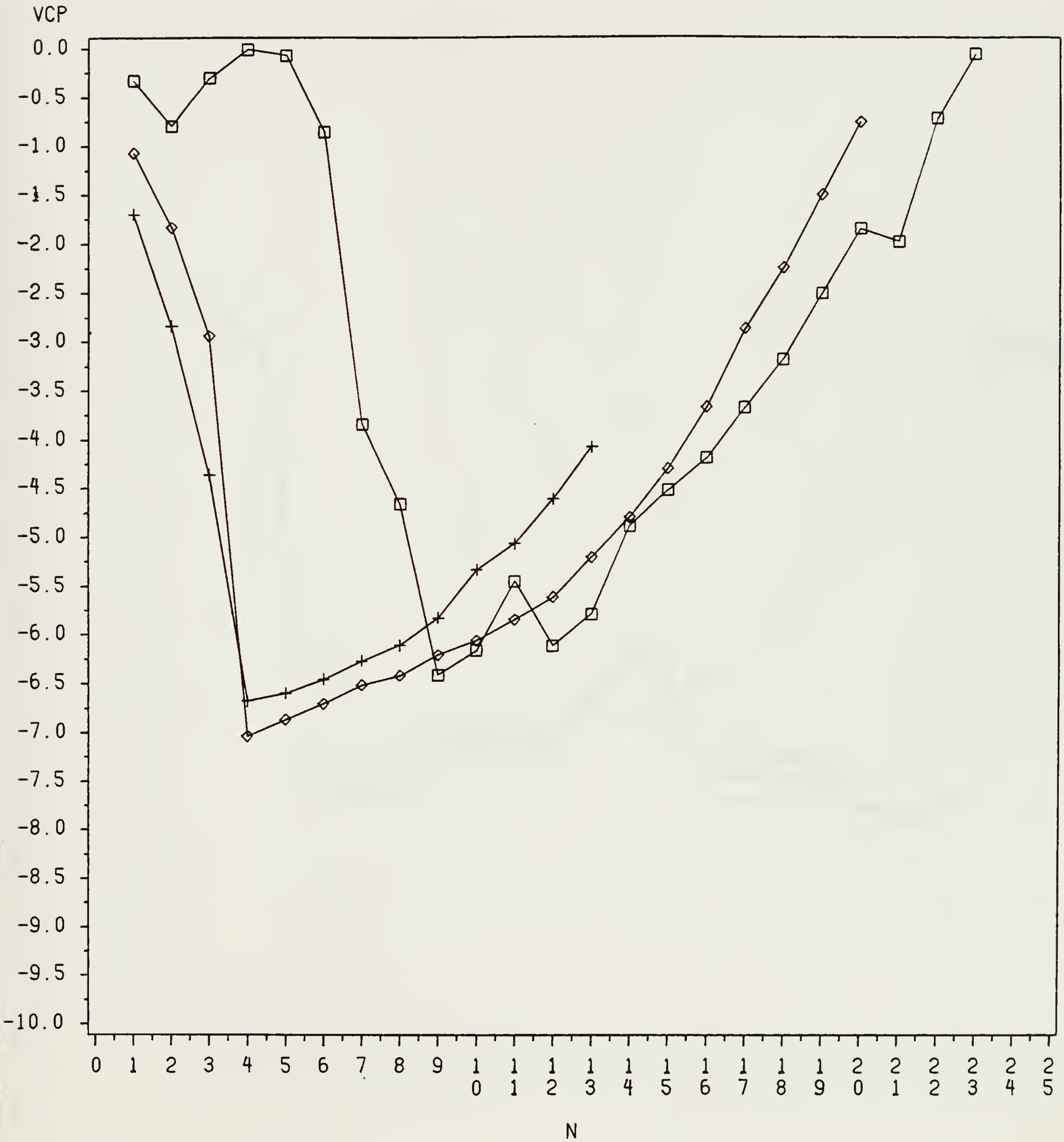
HARRISON CREEK CROSS SECTION
HCVC11



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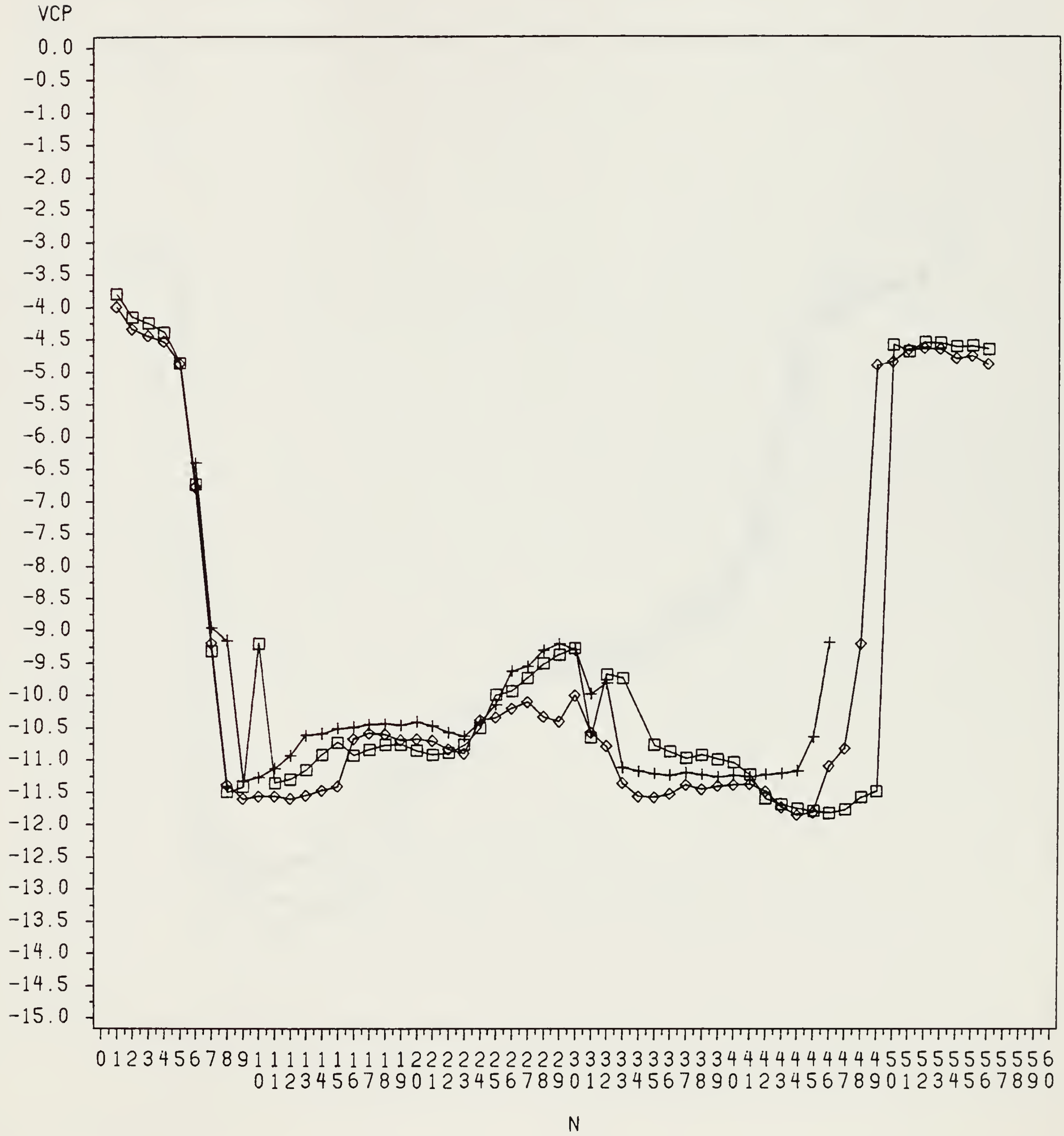
HARRISON CREEK CROSS SECTION
HCVC10



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HARRISON CREEK CROSS SECTION
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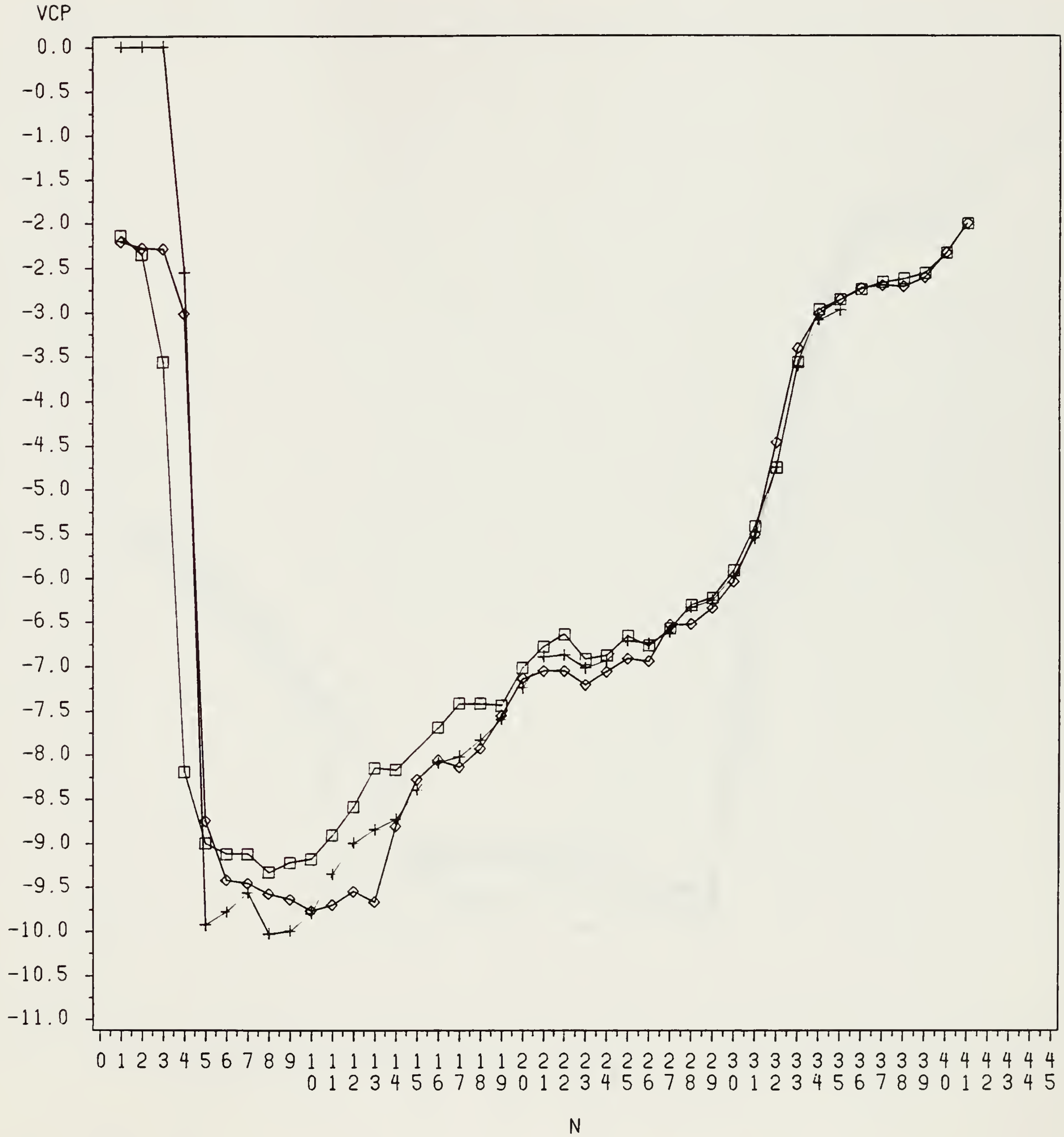

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HARRISON CREEK CROSS SECTION
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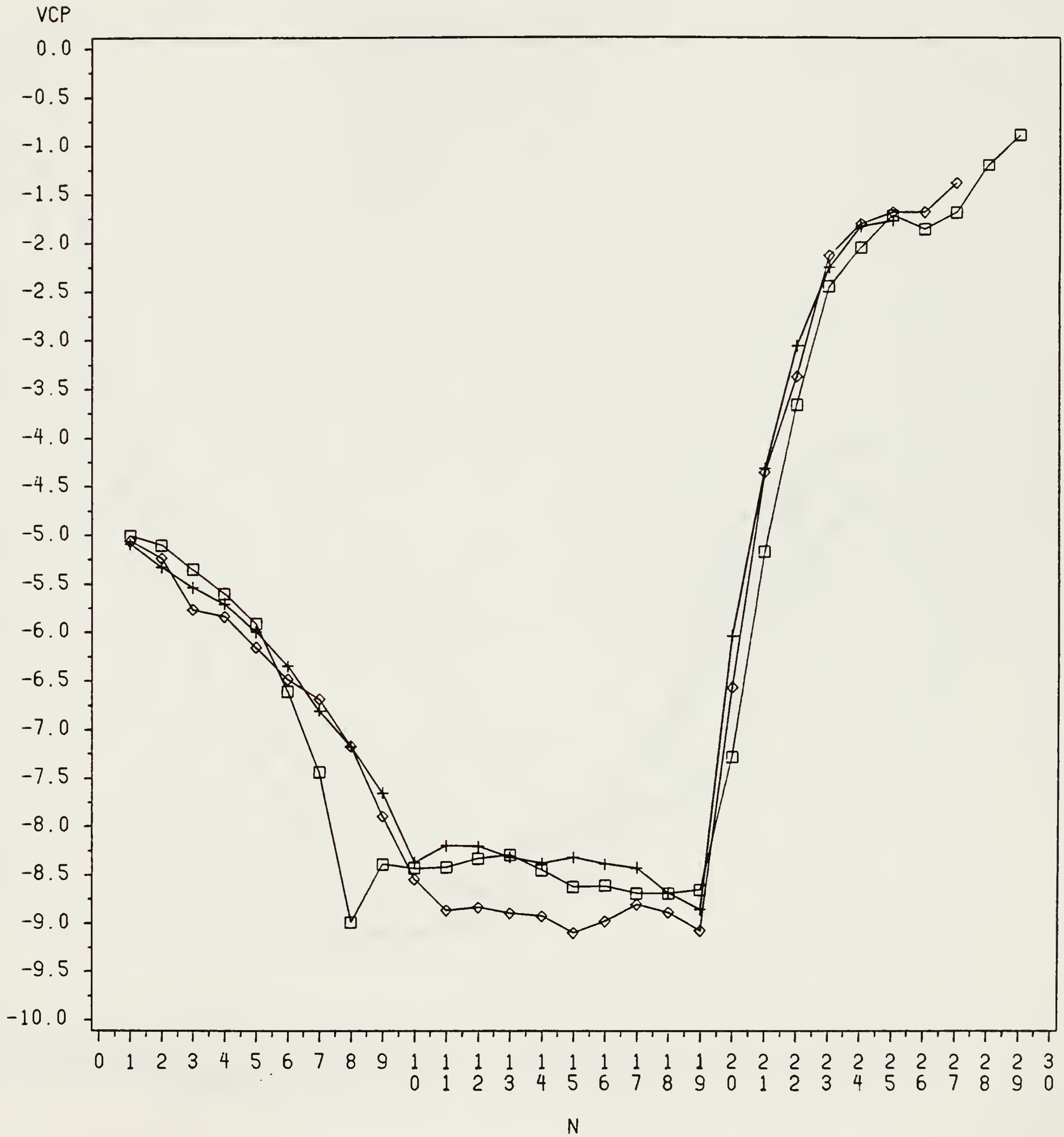

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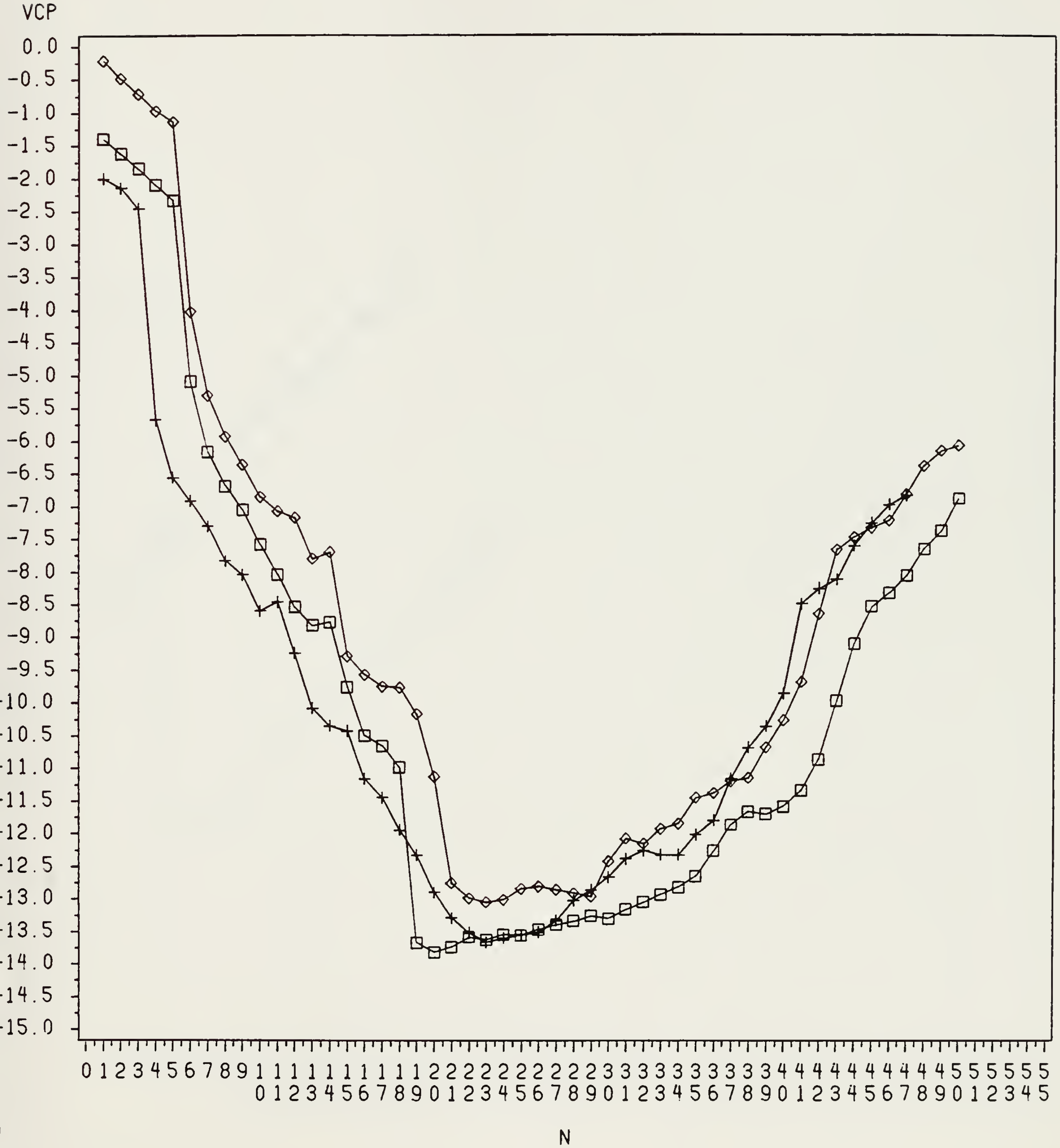
HARRISON CREEK CROSS SECTION
HCVC3



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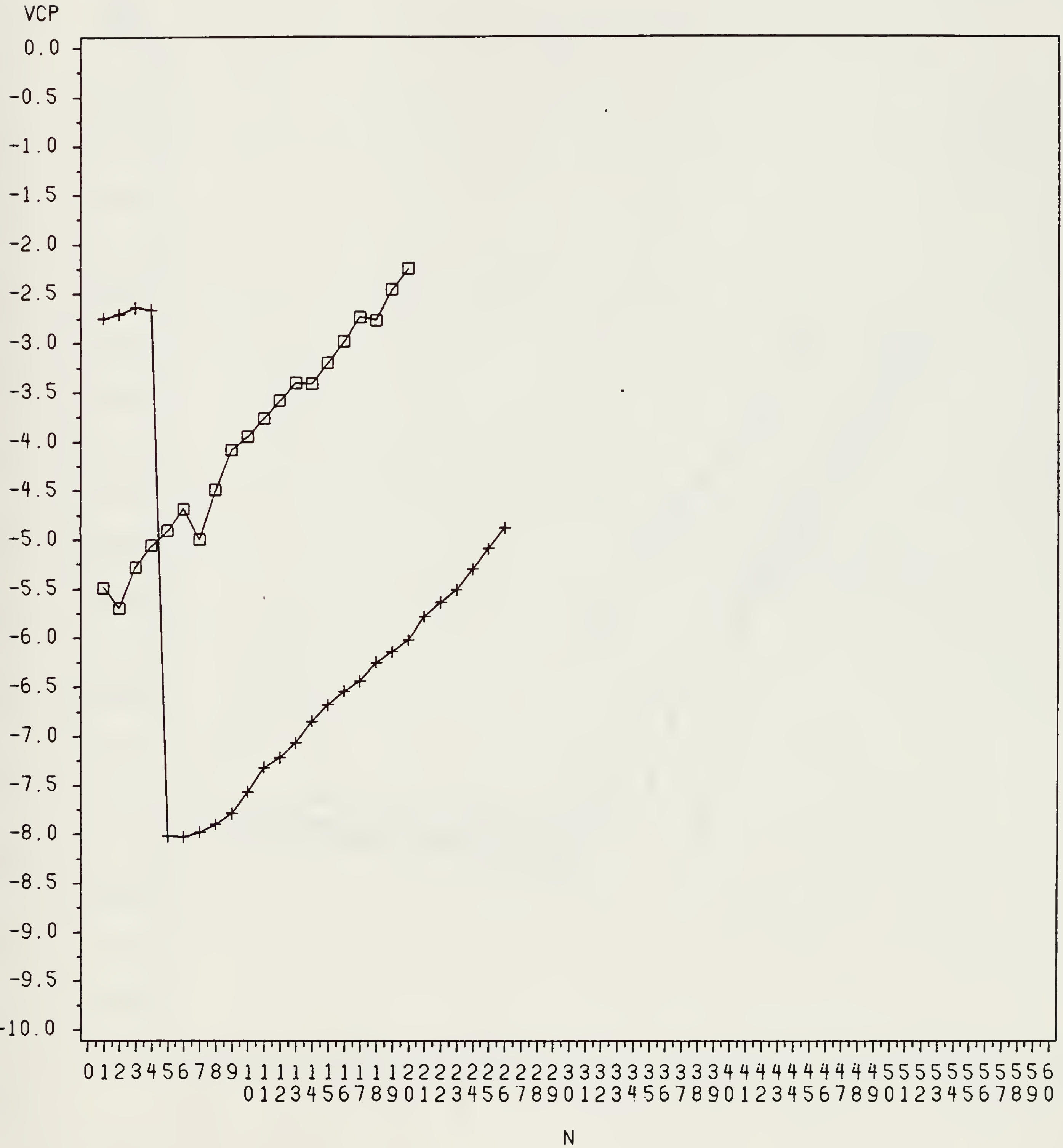
HARRISON CREEK CROSS SECTION
HC103



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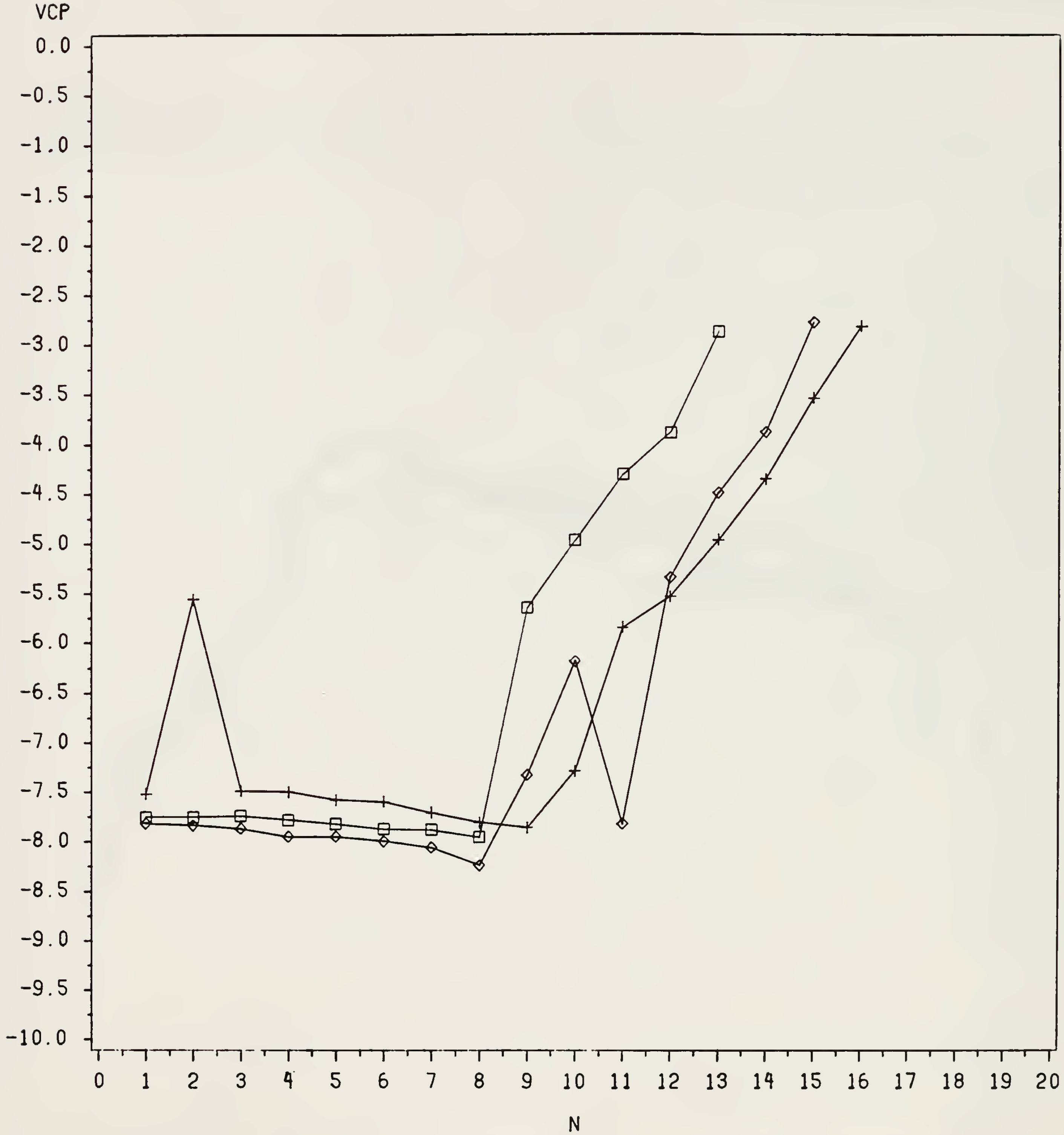
HARRISON CREEK CROSS SECTION
HC96



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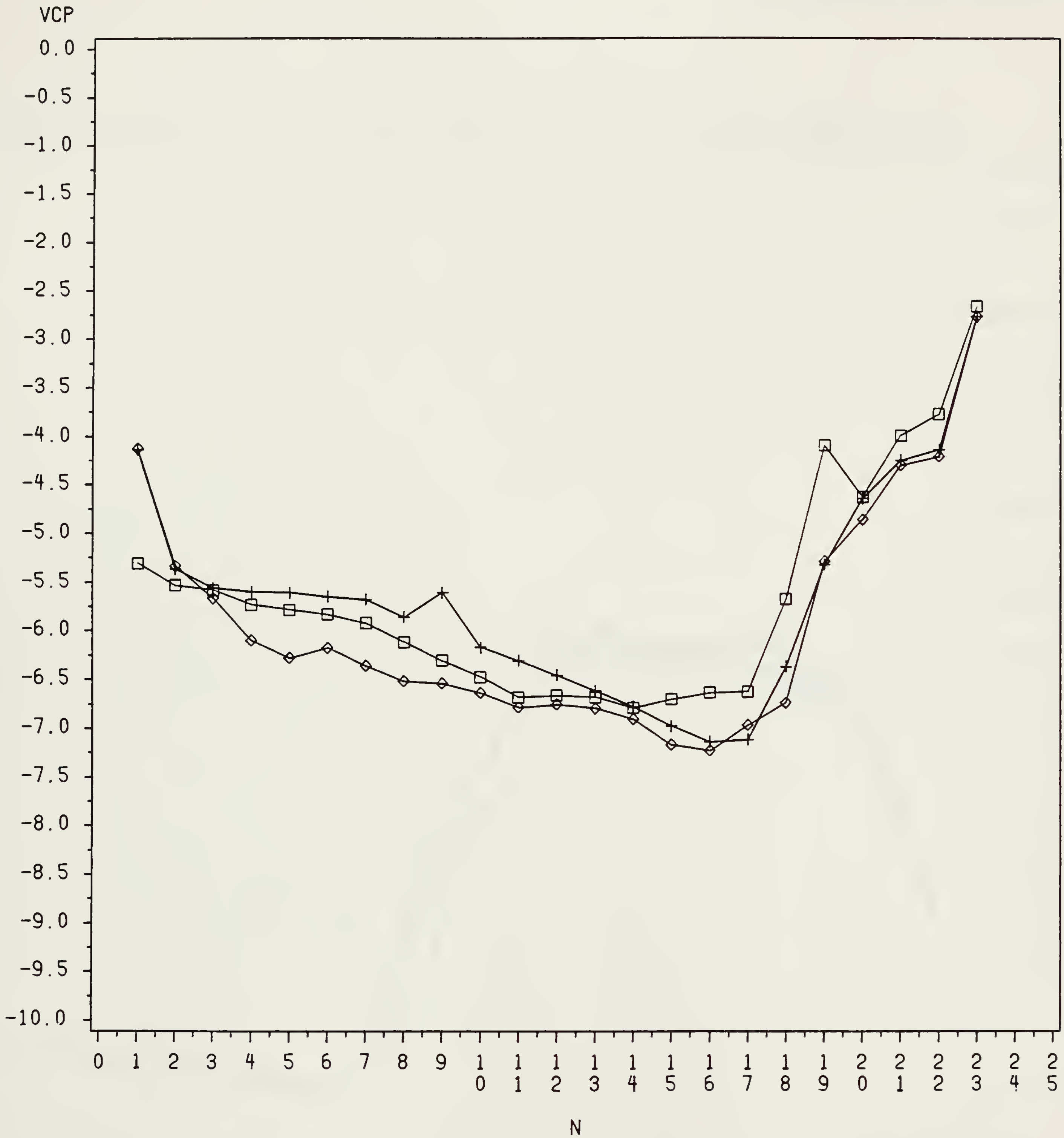
HARRISON CREEK CROSS SECTION
HCVC114



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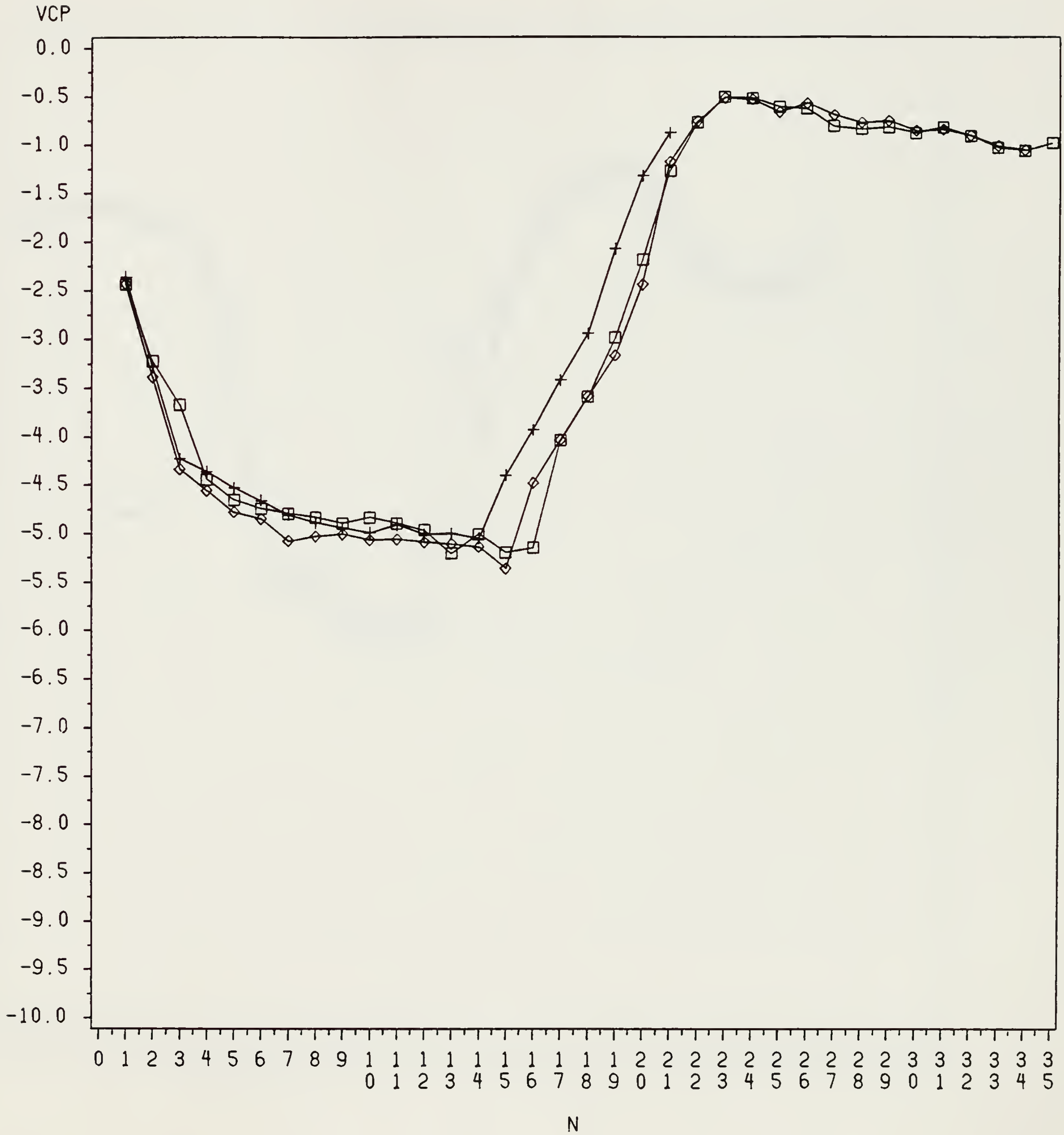
HARRISON CREEK CROSS SECTION
HCVC115



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HARRISON CREEK CROSS SECTION
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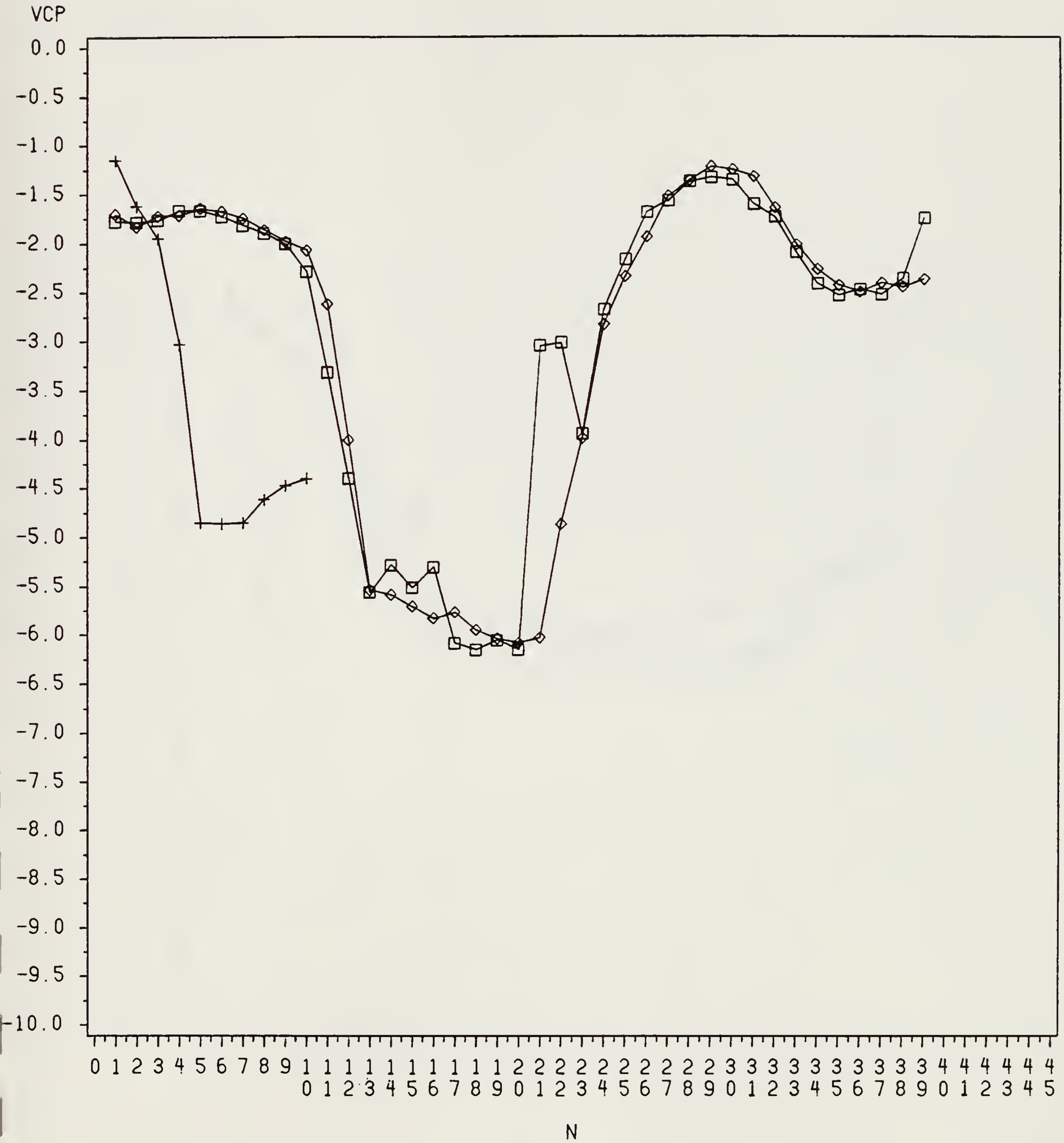

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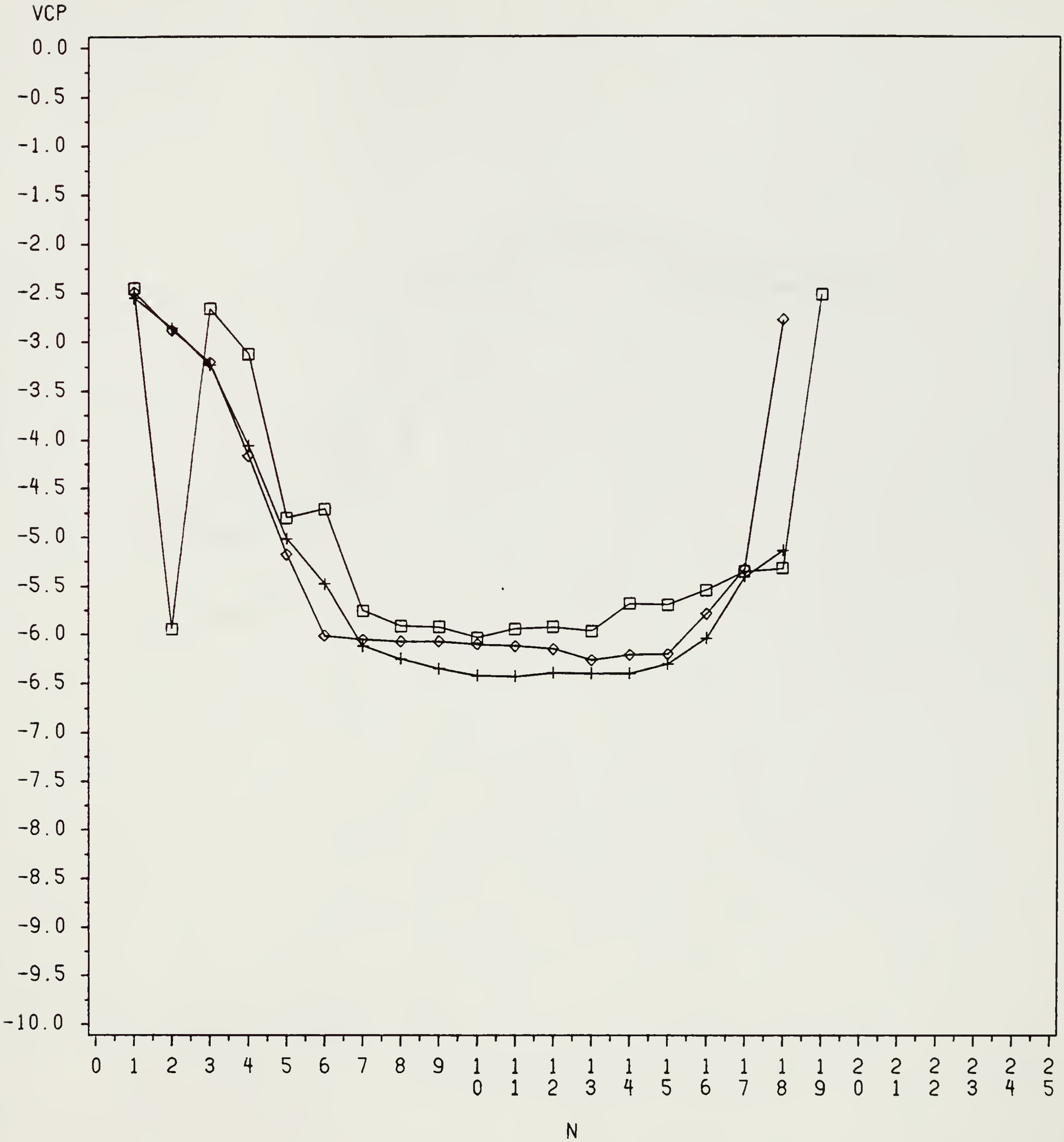
HARRISON CREEK CROSS SECTION
HCVC18



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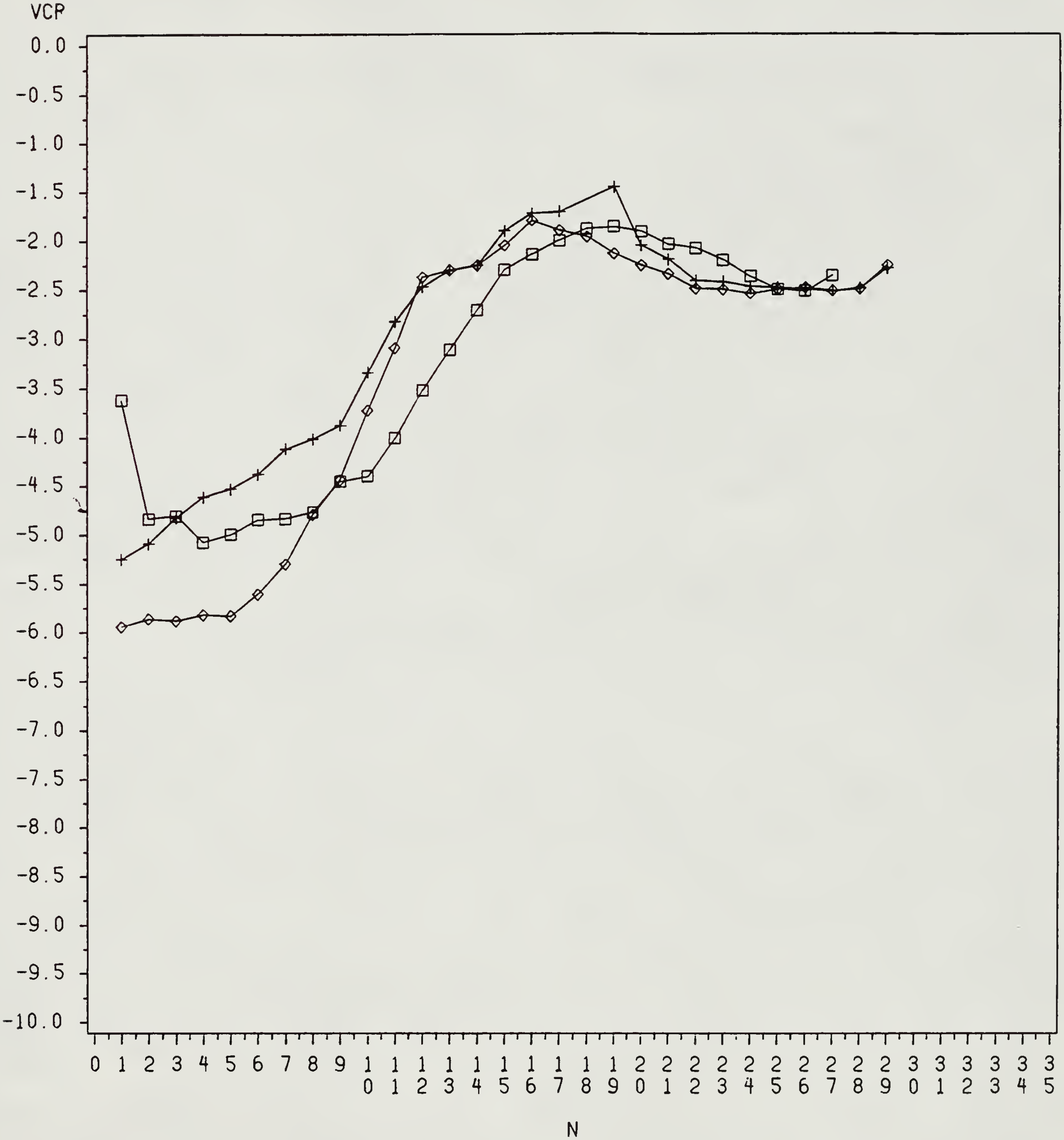
HARRISON CREEK CROSS SECTION
HCVC19



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